

A CRITICAL CLINICAL AND TELEVISION
RADIOGRAPHIC EVALUATION OF
INDIRECT PULP CAPPING.

by

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The Educated Man is one who understands and appreciates the intellectual traditions which produced him, and is willing to give of himself, in his lifetime, in order that he might preserve and extend those traditions.

- José Ortega y Gasset

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TABLE OF CONTENTS

TABLE OF CONTENTS

	Page
INTRODUCTION	1
REVIEW OF THE LITERATURE	
I. Treatment of Deep Carious Lesions	3
II. Further Observations of Changes in Dental Structures	22
III. Serial Radiographic Instrumentation	32
IV. Radiographic Subtraction Technique	33
V. Television Instrumentation	34
STATEMENT OF PROBLEM	37
EXPERIMENTAL PROCEDURES	
I. Clinical Restorative Procedures	38
II. Serial Radiographic Procedures.....	41
III. Television Instrumentation	45
DATA	49
ILLUSTRATIONS	54
DISCUSSION	69
SUMMARY AND CONCLUSIONS	74
REFERENCES	81
VITAE	
ABSTRACT	

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS

	Page
Figure 1. A typical tooth with a deep carious lesion selected for this study	54
Figure 2. Clinical preparation of the deep carious lesion for study in this investigation	54
Figure 3. The components used for obtaining the serial radiographs	55
Figure 4. The individual acrylic film holder with its standardized aluminum step-wedge	56
Figure 5. The individual film holder prepared for clinical use	56
Figure 6. Clinical application of the film holder	57
Figure 7. The instrumentation used for density and linear measurements in the Television Research Laboratory of Indiana University School of Dentistry.	58
Figure 8. Schematic block diagram of television densitometric and linear instrumentation	59
Figure 9. Television densitometric measurement of serial radiographs, photographed from the master monitor	60
Figure 10. The density conversion chart	61
Figure 11. Photographs of master monitor demonstrating television linear measurement of serial radiographs	62
Table I. Mean medication distances, secondary dentin thicknesses, and calcification levels	63
Figure 12. Comparison of average changes in calcification level and secondary dentin thickness with time	64

Figure 13.	Influence of pulpal floor thickness on secondary dentin deposition	65
Figure 14.	Influence of pulpal floor thickness on change in calcification level	65
Figure 15.	Comparison of average rates of change in calcification and secondary dentin.	66
Figure 16.	Influence of pulpal floor thickness on the rate of secondary dentin deposition	67
Figure 17.	Influence of pulpal floor thickness on the rate of calcification change ..	67
Figure 18.	Percent increase in initial pulpal width due to secondary dentin deposition.....	68

INTRODUCTION

A survey of the dental literature revealed a considerable accumulation of evidence to support the technique of indirect pulp capping as a reliable method for conserving the vitality of deeply carious, vital teeth. Reports revealed clinical, radiographic, histologic, bacteriologic, and chemical evidence of physiologic repair.

Much has been said about the observed increases in radiographic opacity of dentinal sclerosis and secondary dentin below deep carious lesions treated with this technique. The treatment and its effects are well documented, but clinical evidence of precise measurement of the degree and rate of dentin changes was found to be lacking.

It is of interest to the dental practitioner to gain insight into an effective method of treating deep carious lesions and the nature of the ensuing reparative activity.

REVIEW OF THE LITERATURE

Vital teeth with deep carious lesions are frequently treated by complete removal of all softened, discolored dentin. The technique of indirect pulp capping has been suggested as a means of treating these teeth and more effectively preserving pulp vitality. This method involves dressing the incompletely excavated caries of vital teeth with a medication which encourages pulpal repair and protects the cavity from further irritation. A thorough review of the literature describing the history, indications, and technique of this useful procedure has been made more meaningful to the reader by including studies of the related biologic and physiologic principles so germane to the understanding of this therapeutic technique.

* * *

A clinician named Foster reported to Harris,¹ in 1850, that he fit a protective gold cap over a thin layer of remaining softened dentin which he allowed to remain over the pulp. He filled the prepared cavity with Hill's stopping. Except for a few exceptions, pulp vitality was regularly preserved. Upon removing these caps after several years, he "found the bone beneath so unyielding and void of sensibility that he was able to introduce a solid gold filling without the cap." He attributed increased treatment success to proper selection of teeth with no history of discomfort.

Tomes,² in 1859, recommended complete removal of softened diseased tooth structure. However, he offered as an exception

discolored dentin of normal hardness, the removal of which would expose the pulp.

Williams,³ in 1899, suggested that it is "perfectly safe to leave a layer of partially softened dentine over the pulp, providing the proper treatment of this softened dentine has been carried out." He selected teeth where no, or slight inflammation of the pulp was suspected. His medicaments, in order of application, were absolute alcohol, oil of cloves, varnish with hydro-naphthol, asbestos paper, cement, and a restoration of silver amalgam or gold.

In 1900, Inglis⁴ suggested that "recalcification" of large areas of soft, decalcified dentin can occur. He proposed that the organic matrix can retain its original form, although deprived of its inorganic content. He hypothesized that this would "indicate that such softened dentin can have its meshes sufficiently refilled with inorganic material in an arrangement sufficiently orderly to restore approximately its original rigidity." The teeth were re-entered after six months to confirm "recalcification."

The earliest reports described the discovery of the value of incomplete caries removal. The techniques employed were empirical but often effective.

TREATMENT OF DEEP CARIOUS LESIONS

Cavity Sterilization

The practice and investigation of sterilization techniques on carious dentin extended from the late 1800's into the 1940's, with most of the interest centered on silver nitrate. Miller,⁵ in 1891, suggested that organisms of any remaining caries could flourish in the best sealed cavity, and therefore thorough sterilization was needed. He applied silver nitrate on a cotton pledget for one-half to one hour. Howe,⁶ in 1917, proposed an ammoniacal solution of silver nitrate, and it was this form of the medicament that became most widely used. A number of other clinical and laboratory studies unfolded in the literature. Among these were the papers of Miller,⁷ Barker,⁸ Ireland,⁹ Prime,^{10,11} Seltzer,^{12,13} Zander,¹⁴ Zander and Burrill,¹⁵ Muntz, Dorfman, and Stephan,¹⁶ and Hardwick.¹⁷

Massler,¹⁸ in 1957, reviewed the effects of silver nitrate and concluded that "it is not rational to pour phenol or caustic silver nitrate into an open wound, in order to destroy the organisms therein if by so doing one also destroys the living cells upon which one depends for the reparative work."

The ability of bacteria to persist under silver amalgam restorations has been demonstrated. In 1943, Besic¹⁹ prepared occlusal cavities in a sterile field of operation. He left some residual caries and re-entered in a year to find no indications of caries progress. There were positive cultures of streptococci persisting in 30 per cent of the cases studied.

Schouboe and MacDonald,²⁰ in 1962, treated 17 mandibular molars in a similar manner. They obtained their cultures from 69 to 139 days after treatment and concluded that "fermentative organisms can remain viable under non-antiseptic fillings for long periods of time." They were uncertain as to whether damaging concentrations of acid were produced. Noonan,²¹ in 1965, prepared 93 occlusal cavities in primary molars, under strictly sterile conditions. Cultures were obtained from two to 60 days after insertion of silver amalgam, and positive cultures were found in 90 per cent of the teeth which initially cultured negative. Silver amalgam restorations did not prevent oral bacterial contamination.

The bactericidal effect of zinc oxide - eugenol cement on bacteria-containing dentin was studied in vitro by Turkheim,²² in 1955. After close contact with the cement for 24 to 48 hours, all heavily inoculated slices of human dentin were rendered sterile. However, under similar conditions, in no case was naturally decayed dentin from extracted carious teeth sterilized.

The bacteriostatic and bactericidal properties of calcium hydroxide were studied in a similar way by Conrado,²³ in 1963. The vast majority of microorganisms cultured from human carious dentin were killed, and the areas of inhibition were of a considerable and significant width. Calcium hydroxide proved to have bacteriostatic or bactericidal properties in

varying degrees, and this was attributed to the high alkaline pH of the material.

A bacteriologic study of deep carious dentin was reported by King, Crawford, and Lindahl²⁴ in 1965. In a sterile field, they sampled the deepest layer of caries from 51 teeth, before restoring with calcium hydroxide - methyl cellulose, zinc oxide - eugenol with accelerator, or amalgam. After 25 to 206 days, the cavities were recultured. The deep carious layer was almost always initially contaminated with microorganisms, but it was rendered sterile, or the number of microorganisms greatly reduced, with zinc oxide - eugenol or calcium hydroxide. Silver amalgam alone failed to produce sterility, but it did reduce the number of cultivable organisms.

With strict attention to asepsis, Aponte and Crowley,²⁵ in 1966, sampled residual carious dentin at various intervals following calcium hydroxide indirect capping, a zinc phosphate cement base, and amalgam restoration. In 93 per cent of 30 primary molars, after six to 46 months, the remaining dentin was free of microorganisms. The dentin of these 30 teeth, upon re-entry, was hard to the touch and had a shiny appearance. Evidence of reparative dentin was present repeatedly in the postoperative bitewing radiographs.

In 1964, McKnight²⁶ inoculated both small exposures and the surrounding cavity floors of dogs' teeth with *Serratia*

marcescens. He sealed the teeth with zinc oxide - eugenol and re-cultured at 144 and 216 hours postoperatively. In these cases of overt pulp exposure, zinc oxide - eugenol did not exhibit a high degree of bactericidal effectiveness.

The consensus of opinion of the authors working in this area is that bacteria persist beneath the majority of amalgam restorations, whether or not caries is allowed to remain. Any sterilizing medicament should be biologically compatible with vital tissue and an effective bactericide. There are indications that calcium hydroxide and zinc oxide - eugenol meet these requirements.

Complete Caries Removal... an alternative

In 1956, Quigley²⁷ reviewed the literature on the treatment of the exposed pulp. He noted that its ability to regenerate after perforation of its dentinal walls had been reported, debated, and denied by various authors in voluminous and contradictory reports. The outlook in such cases, by consensus, was highly questionable.

One technique of maintaining pulp vitality is direct pulp capping. Rosenstein,²⁸ in 1949, evaluated 512 very carefully chosen vital teeth which required direct capping of exposures. He found approximately 90 per cent clinical success in both deciduous and permanent samples. Comparable results were achieved with copper cement, copper cement and silver

nitrate, zinc cement and silver nitrate, zinc oxide - thymol, and zinc oxide - eugenol capping agents. Sawusch,²⁹ in 1963, pulp capped 231 carefully selected teeth with either calcium hydroxide or Dycal. After clinical and radiographic evaluation, he found 80 per cent success with calcium hydroxide and 85 per cent success with Dycal. The degree of success was greater when the preoperative radiograph indicated a less severe carious lesion. Histologic evidence indicated that both calcium hydroxide and Dycal promptly stimulated the formation of a dentin bridge over the exposed area of pulp.

Pulp curettage was described by Chatterton,³⁰ in 1952. He purposely removed a portion of the pulp at the point of exposure of the vital, healthy pulp to one-half the depth of a #6 round bur. A calcium hydroxide dressing was placed over the wound. He evaluated 71 treated posterior teeth representing a wide distribution of pulpal involvement. After one or more years, a success rate of 72 per cent was recorded.

The coronal pulpotomy, utilizing a calcium hydroxide dressing, is another alternative. Teuscher and Zander,³¹ in 1938, demonstrated with photomicrographs that the "formed secondary dentine bridges the living pulp from dentine wall to dentine wall." Zander³² followed, in 1939, with a reported success rate of 71 per cent following calcium hydroxide pulpotomies performed on 150 permanent teeth. Shoemaker,³³ in 1955, performed pulpotomies on 28 well-chosen teeth

with deep caries. A sterile field was maintained during treatment and radiographic and clinical evaluations were made after a mean time of 18 months postoperatively. Upon realizing a success rate of only 39 per cent, he suggested that practitioners were "advocating pulpotomy with more optimism and less proof than was justified." Via,³⁴ in 1955, evaluated radiographs of 103 pulpotomized deciduous mandibular molars for dentinal bridge formation and normal root formation and resorption, after an average waiting period of 25 months. He also found a low success rate of 31 per cent.

Reported evidence shows that the success rate following treatment of exposed, vital pulps with calcium hydroxide is only moderately successful. Attempts to preserve pulpal vitality might be enhanced by the maintenance of the pulpal wall integrity.

Indirect Pulp Capping... case selection and technique

The earliest report¹ of indirect pulp capping pointed to the importance of proper case selection, and other advocates of this technique universally agree. Among them, Brown³⁵ points out that there should be no clinical or radiographic indications of irreversible pulpal changes. The importance of an exact diagnosis of pulpal status is also highly emphasized by Kraus,³⁶ Hess,³⁷ Prader,³⁸ Cantin,³⁹ and Hartsook.⁴⁰ Massler¹⁸

aptly points out that the old aphorism that "an inflamed pulp is a dead pulp" is not true, especially in young and only slightly injured pulps whose reparative potentials are still high.

Seltzer, Bender, and Zientz,⁴¹ in 1963, recorded subjective and objective clinical signs of 166 carious teeth, before removing them for histologic study. They found that a previous history of pain was an important sign of inflammation, and pain is usually associated with a pulp exposure. Under deep caries, they saw anything from no inflammation to chronic inflammation. They agreed with Massler that "inflammation of the pulp is not an irreversible reaction," and the pulp may yet recover following proper restoration.

A similar histologic study was made by Guthrie, McDonald and Mitchell,⁴² in 1965. They observed sections of 53 teeth with deep carious involvement, after recording individual responses to percussion, responses to electric and thermal pulp tests, history of pain, and degree of mobility. Pulp testing was found to be unreliable in determining the degree of pulpal inflammation, as was the degree of mobility or tenderness to percussion. A history of spontaneous pain, especially at night, was a more reliable characteristic of extensive pulpitis than was a history of pain at mealtime. Internal resorption was found exclusively in teeth with extensive inflammation.

In 1966, Luostarinen, Pohto, and Scheinin⁴³ traumatized with diathermy molars of young and old rats, before sealing the teeth with zinc oxide - eugenol. Upon histologic examination, they found necrosis of the dental pulps, especially in the older group where apex formation was completed. They suggested that healing potential was greater in young pulps, especially where root formation was incomplete and metabolism unrestricted.

If the dentin and pulp are to be restored with a "minimum of postoperative scarring," as Masella⁴⁴ suggests, then attention must be paid to scrupulous clinical technique. Best,^{45,46} in the 1920's, emphasized attention to detail and the importance of a rubber dam, dry field, and good lighting. Starkey⁴⁷ also stresses thorough technique and local anesthesia, adding that restorative materials must be placed meticulously and often with a retaining orthodontic band. Bastawi,⁴⁸ in 1963, investigated disintegration and strength characteristics of temporary filling materials. He observed that meticulous placement and smooth surface texture apparently added to the resistance to general disintegration of the material.

Massler^{49,18} has described the technique of indirect pulp capping. The superficial, necrotic caries is removed and the tooth sealed with zinc oxide - eugenol. He states that this will arrest the caries process and sedate the pulp, while the free eugenol sterilizes the dentin. After four to six

weeks, he re-enters to remove the remaining carious, sterile dentin overlying the newly-formed secondary reparative dentin. In every instance, he pays strict attention to biologic principles of cavity preparation, by the "avoidance of excessive surgical trauma or chemical irritation."

Bodecker^{50,51} also used zinc oxide - eugenol in deep carious lesions, especially in young, immature teeth. He saw histologic evidence that this allowed the dentin to become less permeable, thus avoiding severe pulpal reactions. A more regular protective secondary dentin was formed, and patient discomfort was minimized. Massler,⁵² in 1955, observed photomicrographs of rat incisors following treatment with various filling materials. Zinc oxide - eugenol was found to produce the most normal pulp and dentin, while zinc oxyphosphate cements caused considerable, but generally reversible, pulpal damage.

In 1956, Weider, Schour, and Mohammed⁵³ prepared cavities of different depths in 47 maxillary first molars of young white rats. These were restored with zinc oxide - eugenol or Aquadont, or simply left open. Histologic observations showed that reparative dentin formed in all instances. The depth of the cavity was found to be more significant in determining the amount of reparative dentin than were the different fillings or exposure to oral fluids. With increased cavity depth, they noted a thicker layer of more irregular reparative dentin.

Structure regularity of reparative dentin was best with zinc oxide - eugenol and poorest under an open cavity.

Ehrenreich⁵⁴ reported on the microhardness of carious dentin following treatment with calcium hydroxide or zinc oxide - eugenol. Compared to a control group which received no treatment, Knoop hardness readings were statistically higher for only zinc oxide - eugenol. In 1962, Mjor⁵⁵ restored six young premolars with zinc oxide - eugenol. He found a significant increase in the microhardness of dentin, but the increase was much less than what he had found following contact with calcium hydroxide. A year later, Mjor⁵⁶ compared pulp responses to three materials placed over deep cavities prepared in 42 primary molars. After periods of 30 minutes to 88 days, he removed the teeth and made histologic observations. Neither calcium hydroxide nor zinc oxide - eugenol produced significant pulp changes. Amalgam produced more pronounced pulp reactions than either of the other two materials. Stewart and Kramer⁵⁷ histologically compared the effects of zinc oxide - eugenol and calcium hydroxide dressings on the pulps of newly-erupted, prepared human premolars. The teeth were extracted 21 to 84 days following treatment, and they observed no significant differences in pulpal responses. Berk and Krakow,⁵⁸ in 1965, recommended calcium hydroxide for its ability to stimulate secondary dentin formation, initiate sclerosis, neutralize acids of caries and cements, and suppress bacterial activity.

Significant observations of very deep cavity preparations in dogs' teeth were made by Van Huysen and Marzouk,⁵⁹ in 1963, and by Hassan, Van Huysen, and Gilmore,⁶⁰ in 1966. Preparations were performed under a dissecting microscope to a point just short of hemorrhagic pulpal exposure. Following histologic study, they found that "pulp exposures may be microscopic, without hemorrhage, and therefore difficult to detect with the eye." In 1961, Mohammed, Van Huysen, and Boyd⁶¹ compared the effects of several base materials on the pulp under similar deep preparations. One week after treatment, they found calcium hydroxide to be least irritating, in the cases of the microscopic pulp exposures. Zinc oxide - eugenol was destructive in four of five cases, and zinc oxyphosphate cement caused severe pulp necrosis. On the basis of these studies, the routine protection of every deep cavity pulpal wall with calcium hydroxide was recommended. In 1962, Thanik, Boyd, and Van Huysen⁶² reported on a similar histologic study which showed comparable results. In 1965, Inahama⁶³ also found histologic evidence that zinc phosphate cement does not have satisfactory biologic properties for use as an indirect pulp capping material in deep cavities.

Masterson,⁶⁴ in 1966, exposed the pulps of 24 monkey teeth. He placed Calxyl over some and an inert material over the others. Histologic evidence showed excellent healing with Calxyl and no healing with simple pulp protection.

One may surmise from the literature that careful selection of restorable teeth with no evidence of irreversible pulp degeneration is important to successful therapy. Careful attention should be paid to the selection of instrumentation and medications which are biologically compatible with optimal pulpal health. Following removal of the superficial, necrotic, infected layer of caries, one is justified to use calcium hydroxide or zinc oxide - eugenol over the residual softened, discolored dentin.

Studies in Indirect Pulp Capping

In Europe, Bonsack^{65,66,67} was an early teacher of the "natural cap" of zinc oxide - eugenol over softened dentin. He enjoyed nearly 100 per cent success, emphasizing the importance of proper preoperative diagnosis. He found the softened dentin became harder by some unknown remineralization process. Zerosi and Piazzini,⁶⁸ in 1952, renewed dressings of Calxyl every 10 to 14 days, several times. After one year, they used thermal and electric pulp tests to confirm preserved vitality in almost every case. They observed radiographic evidence of dentinal changes. Kraus and Badcock,⁶⁹ in 1953, reported nearly 100 per cent good results with this biologic method of treating deep caries. They discouraged unconditional excavating down to the sound dentin. In 1954, Maeglin⁷⁰ reported clinical success using Calxyl in the

typical indirect technique. Six weeks was the minimal time necessary for any appreciable hardness increase, and dryness of residual carious dentin increased with duration of the dressing. In no case did the carious process progress, and histologic observations were satisfactory. Sowden,⁷¹ in 1956, reported on 4,000 cases treated in a seven year period. His patients ranged from age two to 79, and he observed the carefully selected primary and permanent teeth clinically and radiographically. He would place one millimeter of calcium hydroxide over the deep carious dentin and restore the tooth with silver amalgam. He then returned in two to three weeks to remove the remaining soft caries. He enjoyed almost complete success, and he found radiographic evidence of increased calcification below the medication. Frisbie and Sowden⁷² then saw histologic evidence suggesting that "reconstruction occurs within previously softened and semi-softened carious dentin."

In 1960, Goldman⁷³ reported no failures following "physiological pulp capping" of 30 teeth with zinc oxide - eugenol. His treatment required three visits, and he removed a small amount of caries each time. The teeth were finally restored with zinc oxide - eugenol bases and silver amalgam.

Morgan,⁷⁴ in 1960, reported on clinical and roentgenographic evaluations of calcium hydroxide treatment of vital

pulp exposures in 266 primary and permanent molars. His success rate was about 90 per cent. However, when he would first partially remove the soft caries and place zinc oxide - eugenol about four days before the anticipated pulp exposure, the "recovery period" was followed by almost 100 per cent treatment success.

Mehlum,⁷⁵ in 1960, performed incomplete caries removal on 26 young permanent first molars in which complete excavation would have resulted, in his judgment, in pulp exposure. He placed zinc oxide - eugenol over a calcium hydroxide base and re-entered after three months. He removed the remaining carious dentin to find five pulp exposures. In the remaining 80 per cent of the sample, he found hard, reparative dentin covering the pulp.

In 1961, Damele⁷⁶ reported on 70 cases warranting strong suspicion of pulpal involvement and treated with calcium hydroxide and amalgam. After eight weeks, he removed the remaining caries, obtained radiographs, performed vitality tests, questioned for symptoms, and rendered a prognosis. Pulp exposure was avoided in 85 per cent of the cases. Six months later, all tests were repeated. Ninety per cent of the radiographs showed increased radiopacity adjacent to the pulpal wall, and all teeth in the study remained asymptomatic.

Law and Lewis,⁷⁷ in 1961, studied the effects of calcium hydroxide on 66 deciduous and young permanent teeth where

"pulpal exposure was highly probable but not actually visible in the roentgenograms." Success was determined by the lack of pulpal exposure and x-ray pathology, when the remaining caries was removed six months postoperatively. Seventy-six per cent of the cases met this requirement. Radiopaque areas formed on the pulpal side of residual caries in nearly every case, and the process by which this change occurred was not known.

A study of direct and indirect pulp capping was reported by DiMaggio and Hawes,⁷⁸ in 1962. Of 244 permanent and primary carious teeth with normal pulp tests and radiographs, 92 were selected for complete caries removal and calcium hydroxide pulp capping or pulpotomy. Seventy-five per cent had carious pulp exposures. In 175 teeth, the deepest layer of carious dentin was left in situ, and a calcium hydroxide base and zinc oxide - eugenol were placed. There were no failures in this group. All 21 frank failures in this study occurred in teeth treated with direct pulp therapy. They concluded that, of all extensively carious teeth in this study, 75 per cent would have shown clinical pulp exposure with complete caries removal. By 1963,^{79,80} their sample had reached 724 deeply carious teeth, and they had accumulated histologic evidence from 138 of these. Observations tended to support the original hypothesis that approximately 75 per cent of teeth selected for indirect treatment would have

shown pulpal exposures if all caries had been removed. Associated with direct pulp therapy, they found radicular calcific deposits, early mild chronic inflammation, and a higher early failure rate. Of all teeth under clinical observation, favorable results were as follows: indirect pulp capping, 99 per cent; direct capping, 75 per cent; pulpotomies, 51 per cent. By 1964,⁸¹ observations of 1,048 teeth had continued for two weeks to four years. Frank clinical failures occurred in three per cent of indirect cases, seven per cent of direct pulp cappings, and 19 per cent of pulpotomies. Histologic studies of 314 teeth showed even higher failure rates, but this did not reduce the advantage of indirect pulp capping. Persistence of cultivable organisms for prolonged intervals, following both types of therapy, was shown by simple bacteriological cultures of dentinal scrapings from selected teeth which were re-opened at varying times after treatment.

Success of the indirect pulp capping technique, following use of calcium hydroxide or zinc oxide - eugenol, was confirmed by Herman,⁸² in 1963. The result, in the Pedodontic Clinic of Indiana University, was "a significant reduction in the more radical types of pulp therapy and the conservation of more teeth."

Held-Wydler,⁸³ in 1964, treated deep carious lesions in 41 permanent teeth with zinc oxide - eugenol. After waiting

34 to 630 days, the teeth were removed and histologic sections prepared. The decalcified, softened dentin was not itself bacterial, but it contained bacterial products. Secondary dentin was seen immediately below the cavity, in all but one case, and it appeared thicker when the residual layer of primary dentin was thinnest. In 36 cases, caries left on the cavity floor gave the histologic picture of decalcified dentin. In all but one, pulp tissue retained full vitality.

In 1964, Lorinczy-Landgraf⁸⁴ reported achieving a high success rate after leaving some softened dentin near the pulp. He attributed superiority over the direct capping to the avoidance of exposure and massive inoculation of the pulp.

Kerkhove,⁸⁵ in 1965, compared the effects of zinc oxide - eugenol and calcium hydroxide - methyl cellulose in the indirect technique. Using closed-circuit television densitometric instrumentation to evaluate accurate serial radiographic records of 88 mandibular deciduous and permanent teeth, over a 12 month period, he found a demonstrable increase in radiopacity in 30 per cent of the sample at three months, 40 per cent at six months, and 50 per cent at one year. Four cases were frank failures. The amount of increased radiopacity was very slight and not a routine observation. After one year, he re-entered 42 teeth to find caries arrestment, sound pigmented dentin, and no discernible pulp exposures.

Baume,⁸⁶ in 1965, reviewed his histologic findings, following treatment of deep lesions with zinc oxide - eugenol. Not only did protective secondary dentin form, but small carious exposures and small abscesses became walled off by calcific barriers. Like Bonsack, he saw a reduction in the number of pulp deaths.

Delaney and Seyler,⁸⁷ in 1966, treated 354 deep carious lesions, in teeth which tested vital, with Hydrex, a commercial calcium hydroxide preparation. Their clinical and radiographic observations extended from six to 18 months. A success rate of 88 per cent followed treatment by indirect pulp capping, and direct pulp capping, with complete caries removal and exposure of the pulp, resulted in 76 per cent success. The average failure occurred seven months post-operatively.

Sayegh,⁸⁸ in 1967, reported results following treatment of 145 deep carious lesions. The teeth were extracted from one to 57 months after treatment, and histologic observations were recorded. Compared to the dentinal bridges formed following pulpotomy or direct pulp capping, the indirect technique stimulated production of the greatest amount of new, reparative dentin, in both deciduous and permanent teeth. The greatest thicknesses of new dentin were directly related to thinness of remaining dentin and length of exposure to treatment. The rate of reparative dentin deposition in

108 human teeth had been reported by Stanley, White, and McCray,⁸⁹ the previous year. Little evidence of new dentin below prepared cavities was seen prior to the thirtieth post-operative day. The rate of formation, which averaged 1.4 microns per day, decreased markedly after the forty-eighth day. The factor of remaining dentin thickness, by itself, did not appear to affect "tertiary dentin" production, but the operative techniques inducing considerable trauma were capable of slightly increasing its production.

The literature reflects little doubt and much optimism about the value of indirect pulp capping. With proper case selection, operative procedures, and choice of medication, one should expect to re-enter a treated lesion after two or more months to find, in the majority of cases, an arrested lesion and maintained pulp vitality.

FURTHER OBSERVATIONS OF CHANGES IN DENTAL STRUCTURES

Dental Maturation

In discussing the responses to the indirect capping technique, it is germane to briefly discuss dentin physiology and the normal maturation of dentin. It is these processes which are enhanced and accelerated by the indirect capping technique and sometimes by the caries process itself.

Beust⁹⁰ described the "maturing process" as being a factor of resistance to dental caries. He spoke of his observations that almost 100 per cent of intact adult teeth display some degree of sclerosis, as the early permeability of dentin and enamel to dyes is lost with age. He described the concomitant contraction of the pulp and the acceleration of these processes by caries and other external trauma. Bodecker⁹¹ referred to these changes as a "protective metamorphosis." Bradford,⁹² in 1958, studied ground and decalcified sections of teeth removed from subjects of all age levels, from developing fetuses to aged individuals. He described maturation, from the fibrous framework and undifferentiated ground substance to mature tissue with occluded, sclerotic tubules.

Reaction to the Carious Lesion

In 1928, Fish⁹³ introduced methyl blue dye into the pulps of carious teeth and made histologic observations. He regularly saw a tract of sclerotic dentin running from the lesion to the pulp, bounded internally on the pulpal surface by a sharply defined patch of secondary dentin which was rigidly confined in its area to the tubules which were injured by the lesion. Beust⁹⁴ observed the same tubule obliteration in his observations of permeability and optical properties of ground tooth sections. Bradford⁹⁵ later described Tomes'

fiber of dentin and its "hydrolysis" following the action of acid from caries.

Vissotzky,⁹⁶ in 1945, experimentally induced the formation of secondary dentin in 25 human and dog teeth, using zinc oxyphosphate cement on cavity floors. New dentinal tubules were irregular in number and form. Kronfeld⁹⁷ had also studied protective secondary dentin to find a decreased number of tubules running irregular courses and a decrease in organic content and permeability. He suggested these characteristics were a protective measure against the possible invasion of the pulp by bacteria.

In 1954, Miller⁹⁸ studied microradiographs of transverse ground sections of dentinal tubules. He observed that the translucent area surrounding Tomes' fibril is more highly calcified than the inter-tubular dentin matrix. Serial sections showed fibril size decreasing and translucent area size increasing as they departed from the pulp.

Mjor,⁹⁹ in 1960, saw that ground sections of unaffected primary dentin did not have a translucent zone. It became especially prominent in the tubule walls following calcium hydroxide treatment. He called this tissue change "secondary intratubular mineralization," for it appeared to be due to an additional mineralization in the walls of the dentinal tubules. In 1961,¹⁰⁰ after microhardness tests and densitometric evaluation of microradiographs, using a photovolt densitometer,

he again found evidence to indicate a "highly significant increase in mineralization of calcium hydroxide-covered dentine."

Klein,¹⁰¹ in 1961, used closed-circuit television micro-densitometric instrumentation to study historadiographs of ground sections of treated and untreated deciduous teeth. Using untreated and amalgam-restored control teeth, he noted increased calcification in both peritubular rings and dentinal matrices, especially below calcium hydroxide bases. The same investigator¹⁰² used an Elwood Densitometer to study changes in the dentin of 351 deciduous teeth. Periodic bitewings were taken of 191 teeth, treated with calcium hydroxide and amalgam, and 160 control teeth, restored with amalgam alone. Dentinal sclerosis was observed in 93 per cent of test teeth and only one per cent of the control samples. It was concluded that calcium hydroxide - methyl cellulose stimulates and enhances production of secondary dentin, or sclerosis. He said that dentinal sclerosis is hypercalcification of existing dentin and not a recalcification of carious dentin.

The electron microscope has been used to study dentin. Frank¹⁰³ noted that the peritubular zone was more calcified than the intertubular substance, and it consists of a fibrillar matrix which is often masked by its mineral salts. Awazawa,¹⁰⁴ in 1963, observed deep carious areas, and he

noted diffuse demineralization throughout the dentin. However, collagenous fibrils of the dentinal matrix were remarkably intact in areas of advanced demineralization. Eventually, a "spongy porosity" appears, and the areas become rich in organic collagen fibrils. Crowded microorganisms were seen in devastated carious dentin. The typical picture portrayed "carious demineralization to have taken place here far more remarkably than carious proteolysis." Secondary dentin was found to be composed of large, irregular crystals, with hypomineralization occurring in layers. Tubules were sparse and poorly formed, when present.

Massler¹⁰⁵ has correlated clinical and histologic reactions to caries, to describe the difference between arrested and active caries. The arrested lesion is generally free of bacteria, and it is characteristically non-painful, heavily pigmented, and impermeable. In contrast, the active lesion is a wide, decalcified zone of dentin which is highly permeable to dyes and isotopes. It has a bacteria-rich surface and a sensitive, softened, rather bacteria-free subsurface layer. The deeper layers have been reported¹⁰⁶ to have increasing acidity. Massler describes the caries process as intermittent, with periods of activity and arrest. His observations of the pulp showed that inflammation and odontoblastic destruction were prominent only under very deep, active lesions. Yoshida and Massler¹⁰⁷ reported similar

findings under deep caries. They saw a basophilic line, suggesting hypercalcification, at an early stage, at the pulpal border of the primary dentin. The amount of reparative dentin formed could be correlated with the depth of the lesion. "The human pulp showed a high reparative potential." In 1965, Sarnat and Massler¹⁰⁸ recorded their electron microscope observations. In the bacteria-free arrested lesions, the intratubular zone appeared more mineralized, and the deeper intratubular areas were often hypermineralized and obliterated, or sclerosed. They emphasized the differentiation of two distinct layers in the active lesion: the bacteria-rich infected zone, and the practically bacteria-free, affected zone, underneath. They hypothesized that the pigmentation of the arrested lesion may be related to degenerative changes in bacteria or their products. Earlier, Johansen¹⁰⁹ had suggested changes in matrix amino-acid composition, food, and tobacco as other possible sources of pigmentation.

There is evidence that dentinal sclerosis and deposition of secondary dentin occurs with age, as a function of normal dental physiology. The carious process causes a depletion of inorganic material from the organic matrix and tubules. With arrestment of the carious lesion, as occurs following treatment by indirect pulp capping, the precipitation of protective secondary dentin and tubular sclerosis is enhanced.

Other Physical and Chemical Characteristics

In 1966, Malone, Bell, and Massler¹¹⁰ reported on some physicochemical characteristics of active and arrested carious lesions of dentin. The origin and nature of pigmentation was not identified, but infrared spectroscopy and nitrogen analyses indicated a higher organic composition in active caries than in dentin with arrested carious lesions. Flame spectroscopy showed increased calcium in the arrested lesion, but the content was less than in normal, non-carious dentin. The findings pointed to the possibility that a remineralization occurs. They suggested that "the increased hardness of the arrested dentinal lesion," also specifically identified by Fusayama, Okuse and Hosoda,¹¹¹ in 1966, "is probably related to an increase in calcium phosphate, rather than dehydration of the organic matrix alone."

In 1940, Bird, French, Woodside, Morrison, and Hodge¹¹² showed that the composition of both enamel and dentin do not vary significantly between the primary and permanent dentition. Therefore, samples from each group may be meaningfully compared, in evaluating carious lesions. In 1965, Little, Dirksen, and Schlueter¹¹³ performed chemical analyses of 90 carious dentin samples excavated directly from the mouth. The deeper carious layers were richer in minerals, and all samples were far less mineralized than normal dentin. The major portion of the ash was calcium and phosphorus, with

calcium predominating somewhat at the deeper levels. In 1965, Eidelman, Finn, and Koulourides¹¹⁴ performed indirect pulp capping procedures, with Dycal and amalgam, for 30 teeth with deep carious lesions and healthy pulps. After substituting pink wax for Dycal in five control teeth, they spooned out and analyzed residual caries at two, four, six, eight, and 12 weeks. Each time, five teeth were sampled. The carious samples were dehydrated and weighed, after which the mineral phase was dissolved out with perchloric acid. Using a spectrophotometric technique, quantitative analyses showed a highly significant increase in phosphorus content, with no significant changes in the control group. Insufficient evidence was available to correlate the length of time of the treatment and the degree of remineralization of carious dentin. All but one tooth was sound at the completion of the study, and they concluded that preliminary evidence supports the hypothesis of carious dentin remineralization.

It is meaningful to review possible pathways of origin for the proposed remineralization. In 1939, Schour¹¹⁵ pointed out that, except for sclerosis and secondary dentin formation, tooth structure is not subject to modification in structure or calcification, especially from without. In 1941, Wasserman, Blayney, Groezinger, and DeWitt¹¹⁶ injected radioactive phosphorus into 10 adult dogs. They found that a quick distribution of phosphorus throughout the dentin takes

place in pulpless and traumatized teeth. They did not know if this transfer was metabolic, physical absorption, or simple chemical combination. In 1942, Volker¹¹⁷ fed radioactive phosphate to experimental animals. Upon measuring radiation emission from the recovered teeth, he found that the erupted tooth is subject to phosphate metabolism, however slight. The pulp, he stated, was the most probable pathway. Sognnaes and Shaw,¹¹⁸ in 1952, injected radioactive phosphorus into Rhesus monkeys. Among their findings, they observed that blood-borne radiophosphorus was the major source for dentin.

Although evidence of radioisotope investigation of indirect pulp capping is lacking, some studies of the direct technique have been recorded. Sciaky and Pisanti¹¹⁹ dressed 42 amputated pulps of dogs with radioactive calcium hydroxide. They made autoradiographs of ground sections to find that radiocalcium was confined to the area of the calcium hydroxide dressing. There was slight diffusion of Ca^{45} along the adjacent dentino-enamel junction, but none was demonstrated in the newly-formed roof. In 1964,¹²⁰ they injected labeled calcium hydroxide intravenously to once again find evidence that "the calcium in the protective wall comes from the bloodstream." Contradictory evidence was presented by Stark, Myers, Morris, and Gardner,¹²¹ in 1964. They exposed 20 pulps of Rhesus monkeys and capped them with radioactive

calcium hydroxide. Autoradiographs demonstrated calcium migration, for scattered areas of radioactivity in the pulp occurred in 25 per cent of the sections studied. The results of their study would tend to substantiate a hypothesis that some calcium from the medication may enter into the formation of reparative dentin.

Two in vitro studies demonstrating remineralization were reported in 1960. Blake¹²² perfused sections of undecalcified teeth for seven days with a "calcifying solution." Radiographic and microradiographic observations revealed that a preponderance of the dentinal tubules had become completely occluded with a relatively dense radiopaque material. The appearance was similar to that seen in sclerosed dentin. Solomons and Newman¹²³ induced crystal formation in demineralized dentin with inorganic solutions and simulated ultra-filtrates of serum. This precipitation of calcium phosphate in a mineral-free, acellular system with physiologic solutions led the authors to further support the hypothesis that "steric properties associated with epsilon-amino groups may be responsible for the specific ability of dentin collagen to induce crystal formation."

There is some chemical, physical, and radiographic evidence to support the hypothesis that carious dentin undergoes an increase in calcification as it is being "arrested." If inorganic material does, in fact, enter from the blood-

stream, it may possibly precipitate in either remaining healthy dentin or in partially demineralized, intact tubules.

SERIAL RADIOGRAPHIC INSTRUMENTATION

Useful advances in the technology of radiographic technique and interpretation have been reported. Using an apparatus which fixed the film in the mouth in a standard position, Dirks, Winkler, and van Aken,¹²⁴ in 1958, obtained serial identical roentgenograms. The reproducibility, they said, was 96 per cent, while caries could be estimated with a standard error of the mean of 0.3 per cent. In the same year, Eggen¹²⁵ reported on a technique of standardized, repeatable intra-oral roentgenographic exposures. Benkow¹²⁶ described a combination film holder - bite block used to serially reproduce angulation, anode-film distance, and film-tooth relationship. Since the target-film distance was increased and maintained with a coupled distance rod, improved geometric sharpness was noted. Hollender and Lantz,¹²⁷ in 1963, developed their version of a technique to maintain projection geometry and photographic density. A compound impression facilitated periodic return of the coupled film holder to dog mandibles. For anatomical reasons, they felt the lower premolar and molar regions were best suited for serial "identical roentgenography." The precision and

reliability of the technique was confirmed by parallax measurements of serial exposures. They referred to the previous work of Bjorn¹²⁸ and Berghagen.¹²⁹ In 1964, Carlsson and Benkow¹³⁰ performed statistical analyses of radiographs exposed with the use of the apparatus which Eggen developed. Since the film was not physically coupled to the tube head, judgment was used to align the tube direction. Following intra-oral radiographic exposures, measurements of the extracted study teeth were compared to film image dimensions. They complimented the accuracy and simplicity of the technique as a useful tool in clinical studies.

RADIOGRAPHIC SUBTRACTION TECHNIQUE

In 1935, Ziedses Des Plantes¹³¹ had used individual impression compound trays to accurately position patients' heads for serial radiographs. But his main purpose was the development of a technique he called "subtraktion." He elaborated on his progress in 1961.¹³² Oldendorf,¹³³ in 1964, explained how the technique of subtraction can display and accentuate the differences between two radiographs which differ only in certain details of interest. He described how the negative, or "diapositive," which must be a precise densitometric inverse of the original, is exactly registered

with the film from which it is to be subtracted. He suggested that registration is best accomplished by superimposition of clearly seen anatomical structures. Auto-subtraction of a single film was described as a technique for emphasizing subtle information. Chynn¹³⁴ pointed out that this approach can eliminate, or subtract, unwanted overlapping shadows and bony structures from a roentgenographic film. Crittenden and Stern,¹³⁵ in 1966, emphasized the importance of stability of both patient and tube between exposures of films to be subtracted. Dilenge and Metzger¹³⁶ again confirmed the value of this method for determining tissue changes. A "second-order subtraction" technique, utilizing a second diapositive, was described by Hanafée and Shinno,¹³⁷ in 1966. They were able to almost completely eliminate unwanted hard tissue shadows. Radiographic subtraction by color addition was reported by Frey and Norman¹³⁸ and by Wise and Ganson.¹³⁹ It offered a dramatic contrast of hard and soft tissues.

TELEVISION INSTRUMENTATION

It was previously mentioned that Klein,¹⁰⁰ in 1961, and Kerkhove,⁸⁵ in 1965, successfully used closed-circuit television instrumentation in dental research for densitometric evaluation of radiographs. In 1963, Klein¹⁴⁰ described how

an oscilloscope, when introduced into the closed-circuit television system, enables one to select any one of 500-1000 lines of scan from the television image of the radiograph for evaluation. The line, which appears on the monitor as an intensified blank line; may be reduced to an illuminated reference marker dot for more specific location and evaluation of a given area. The selected line and point also appear on the screen of the oscilloscope as a waveform depicting variations in the relative image densities across the scan line. These waveforms represent the intensity of electrical impulses, in millivolts. The oscilloscope pattern may be viewed by a second camera and its image inserted, by the use of a special effects generator, into the composite picture at the master monitor. Monitoring this waveform assists the operator in selecting specific points on the image being studied for measurement of density or linear distances.

In 1966, Klein and MacPherson¹⁴¹ described how a pulse generator - mixer system can generate onto the screen a calibrated line of reference marker dots for more accurate evaluation of distances. A digital readout of video voltages, and thus of either density or linear distances, is facilitated by this innovation. The same investigators¹⁴² described how intra-oral microm measurements can be performed by photographing stored television microscope images and the accompanying calibrated scan lines. With this instrumentation, Horwitz,¹⁴³

in 1966, measured marginal deterioration of dental restorations. Klein,¹⁴⁴ in 1967, published a comprehensive report of his progress in applying television instrumentation to intra-oral microscopy, linear and density measurements of radiographic records, and radiographic subtraction.

The value of subtraction, using television instrumentation, was reported by Holman and Bullard,¹⁴⁵ in 1963. Succeeding reports by Holman,^{146,147} Takekawa and Holman,¹⁴⁸ and Wallman and Wickbom¹⁴⁹ reflected excellent results with electronic image reversal, using two cameras and a single monitor. Television subtraction was successfully employed by Aguiar,¹⁵⁰ in 1966, to visually clarify medullary spaces in spongy bone. Once defined, these spaces were accurately measured with a calibrated scan line, as described above, which was generated onto the screen of the monitor. As advantages of the electronic subtraction readout technique, investigators have cited improved contrast, image adjustment, the option of magnification, and the rapidity with which satisfactory subtraction studies may be accomplished. Landmarks may become more clearly defined, and radiographic diagnoses may be performed with greater confidence.

STATEMENT OF PROBLEM

It was the intent of this study to quantitatively measure the rate and amount of calcification changes and deposition of secondary dentin produced by the physiologic reaction of the dental pulp to the indirect pulp capping technique. These measurements were accomplished by utilizing television linear and densitometric measurement instrumentation to critically evaluate standardized serial radiographs of young teeth which were treated by indirect pulp capping.

EXPERIMENTAL PROCEDURES

The description of the methods and materials involved in this study has been divided into three parts:

1. Clinical Restorative Procedures

The criteria for selection of teeth, cavity preparation, and the placement of restorative materials

2. Serial Radiographic Procedures

The technique of obtaining the standardized serial radiographs

3. Television Instrumentation

A description of the electronic instrumentation used of making linear and density measurements

CLINICAL RESTORATIVE PROCEDURES

The Sample

In this study, because the Hollender¹²⁷ radiographic technique is best standardized in the mandibular arch, 50 mandibular posterior teeth of children aged three to 12 were carefully selected. The teeth included 24 primary first molars, 16 primary second molars, nine permanent first molars, and a double-rooted first bicuspid.

Additional criteria for selection were:

1. Deep caries, with possible exposure of the dental pulp, as judged by critical examination of periapical and bitewing radiographs.
2. No history of painful pulpitis or clinical evidence of irreversible pulpal inflammation.
3. No evidence of radiographic periapical pathology.
4. Absence of percussion sensitivity.
5. Sufficient clinical crown remaining to permit isolation and placement of an amalgam restoration which would not obliterate subsequent radiographic observations of pulpal and dentinal changes below the restored carious lesion.

The Cavity Preparation

Prior to the operative procedure, the initial serial radiograph was exposed (Figure 1). Local anesthesia was achieved with a mandibular block injection of two per cent Xylocaine Hydrochloride, with 1:100,000 epinephrine.

The involved teeth were isolated with a rubber dam, and the cavity outline, as described by McDonald,¹⁵¹ was established using an air-driven handpiece rotating at 300,000 r.p.m. An air coolant was employed. Large round burs, rotating at very slow speeds, and spoon excavators were used to remove all but a thin layer of soft, carious dentin overlying the pulp. That last amount of carious dentin which remained was judged to be

that thickness which, if removed, would cause a clinical exposure of the pulp. The central portion of the pulpal floor was then painted with a radiographic indicator paste of water-soluble barium sulphate.* (Figure 2) This paste facilitated radiographic identification of relationships between the cavity floor and other significant landmarks. The rubber dam was removed, the teeth isolated with cotton rolls, and the second radiograph was taken.

Following placement of a new rubber dam, the cavity was carefully cleansed of barium sulphate with warm tap water and dried with a warm air stream. A creamy paste of chemically pure calcium hydroxide and one per cent methyl cellulose was placed over the residual caries, to a thickness of approximately one millimeter. A small cotton pellet was used to apply a single coating of Copalite** over the calcium hydroxide methyl cellulose. In some very deep preparations, bases of zinc oxyphosphate cement*** were placed. Finally, restoration was completed with mechanically triturated,**** hand condensed fine-cut amalgam,***** in a 1:1 mercury-alloy ratio.

Subsequent serial radiographs were planned at post-operative intervals of one, three, six, nine, and, in some cases,

* Micropaque Powder, Demancy & Co., Ltd., England.
** Cooley & Cooley, Ltd., Houston, Texas.
*** Fleck's Cement, Mizzy, Inc., Clifton Forge, Pa.
**** Wig-L-Bug Amalgamator, Crescent Dental Mfg. Co., Chicago, Ill.
***** Fine Cut Alloy, The L.D. Caulk Co., Milford, Del.

12 months. At the final visit, the usual serial radiograph was made. Whether it was after nine or 12 months, the teeth were once again anesthetized, isolated, and re-entered. Following complete removal of all restorative materials, all of the residual caries was removed. The nature of the cavity floor and the presence of any pulpal exposures were recorded. Serial radiographs of the study teeth, with caries removed, were exposed both with and without the barium sulphate indicator paste on the 'new' floor. Following replacement of the rubber dam, the paste was thoroughly flushed from the preparation, and the tooth was permanently restored with amalgam, in the manner previously described. When indicated, stainless steel crowns were placed. Pulpal exposures dictated more radical pulpal therapy.

SERIAL RADIOGRAPHIC PROCEDURES

Previous work leading to the development of this technique has been described in the literature review. In this study, a method was devised for accurately and firmly coupling each individual film holder to the head of the x-ray tube. A film holder for either the left or the right side was constructed for each quadrant in which one or more teeth were to be studied. The possible variables of exposure time, developing time, and temperature and age of the solutions were

anticipated. As a control and standard, into each film holder was incorporated a precisely machined aluminum step-wedge.

Description of the Apparatus (Figures 3 and 4)

1. A square metal cone,* with a slot in one corner for snugly securing the distance rods, was attached to the head of a 60 kilovolt, 10 milliampere x-ray unit.**
2. A "right" and "left" constant-distance rod, 11 3/8" in length, was constructed of 1/4" square aluminum stock.*** Each was carefully bent in two planes to place the film holder in the central beam of radiation. A rectangular slot was precisely placed in the end of the rod, to allow a sound fit over the end of the aluminum step-wedge at the film holder.
3. For each film holder, a precise aluminum step-wedge was machined from stock 3/8" by 1" aluminum bar material.**** Each of the five steps which were cut measured four millimeters square. Four of the steps varied from each other by a depth of two millimeters, and the last interval was only one millimeter.

* X-ray Mfg. Corp. of America, Great Neck, N.Y.

** X-ray Mfg. Corp. of America, Great Neck, N.Y.

*** Kaiser Aluminum

**** Kaiser Aluminum, Type KACC-00A-270-6061T6

4. The 'right' and 'left' individual film holders were fashioned from several fitted acrylic pieces to provide a film-retention slot, a step-wedge housing, and a distance rod support assembly oriented 90 degrees to the film. The film-retention slot provided an area one millimeter deep and 24 millimeters wide through which the film packet was closely guided. The superior and inferior sides of the step-wedge housing were constructed of a three millimeter thickness of acrylic, and these acted as bearing surfaces for the individual compound bites, or indices. The distance rod support assembly was accurately constructed by allowing cold-cure acrylic* to cure about the properly positioned, lubricated distance rod. The resulting slot receptacle was selectively hand-filed and dry Teflon lubricant compound** used to insure an ease of insertion and patient comfort. All sharp edges of acrylic were polished, and the lingual extension of the holder was rounded to prevent injury to the floor of the mouth.

* Plas-T-Pair, Rawn Co., Inc., Spooner, Wisc.

** Glide 200, Chemplast, Inc., East Newark, N.J.

Clinical Preparation and Use of the Apparatus (Figures 5 and 6)

To accustom the patient to the procedure, an individual film holder for the appropriate side was selected and positioned in the mouth adjacent to the teeth to be studied. The holder was withdrawn and a vaselined film packet was placed in its slot. A roll of warmed impression compound* was then wrapped around the holder, and the unit was replaced in the mouth. The patient was directed to occlude into the thermo-plastic material and maintain that position while the compound cooled. Excess compound was removed from around the reproduced occlusal patterns, as were positive reproductions of large carious lesions.

Prior to making a typical serial exposure, a new No. 0 film packet** was placed in the holder. The unit was placed in the mouth and maintained with stability by the patient's occlusion of maxillary and mandibular teeth. The metal cone, distance rod, and the holder's support assembly were visually aligned then mechanically joined in a stable coupling. Duplicate films were exposed at each step, for later use in subtraction readout observations.

A standard exposure time of 1.5 seconds was practiced in every instance. All films were developed for five minutes

* Kerr's Compound, Kerr Manufacturing Co., Detroit, Mich.
** Kodak Periapical Ultra-Speed No. 0, Eastman Kodak Co., Rochester, N.Y.

at 68⁰ Fahrenheit and promptly fixed for 20 minutes at the same temperature. They were then washed in room-temperature water for 30 minutes and allowed to dry.

TELEVISION INSTRUMENTATION

The electronic measurements for this study were performed in the Television Research Laboratory of Indiana University School of Dentistry. The specific components (Figure 7) and an electronic schematic block diagram (Figure 8) are illustrated.

Each radiograph studied was placed in an Optoliner* which illuminated the film with a flat light and sent the image through its lens package to a television camera.** A second Optoliner and camera were employed for subtraction procedures. Television images were observed at the master monitor*** at 14X magnification.

Densitometric Instrumentation and Measurement Procedures

Measurements of light transmission through steps number two and four of the step-wedge were recorded for each serial radiograph, using the MacBeth Quanta-Log densitometer.**** Before the television evaluation of each film, the range of the density amplifier unit was carefully calibrated to coincide with that of steps two and four, as measured by the

* TVO 1000 Optoliners, Photo Research Corp., Hollywood, Calif.

** VCF-3 Cameras, Sarkes Tarzian, Inc., Bloomington, Ind.

*** Model CMC, Conrac Div., Giannini Controls Corp., Glendora, Calif.

**** MacBeth Quanta-Log, MacBeth Instrument Corp., Newburgh, N.Y.

Quanta-Log densitometer.

As each film was viewed on the television screen, an illuminated line of scan across the screen was manually selected for investigation. The same oscilloscope which generated the line provided an adjustable spot along the line which indicated the exact point at which density of the viewed radiographic image was to be measured. The actual electronic measurement was sent to a digital readout unit. The readout was viewed by a second television camera and inserted into the composite image, with the use of a special effects generator.

After calibrating the density amplifier with steps two and four of the radiograph, the adjustable spot was positioned to sample densities (Figure 9) of the pulpal floor under the lesion and in a comparable, unaffected control area of dentin. The same areas were measured for all films of a given series. Due to variations in general density between films, characteristics of light transmission, and thus of density measurements, changed. To minimize the effect of these discrepancies on final density comparisons, a density conversion chart (Figure 10) was constructed to plot opacity against transmission on a 3 X 3 cycle logarithmic scale. A linear density scale was derived from density-opacity-transmission tables¹⁵² and plotted on the graph. An arc was struck to represent the average value of step two for the entire study. An identical

but sliding density scale was constructed to represent film densities. For each film, the original Quanta-Log density readings were located on the sliding scale. Step two was positioned on the arc at the level of its corresponding opacity reading. The sliding scale was then rotated slightly until the step four readings also matched in a similar fashion. The measured television values for the control and sample areas were then located on the sliding scale and corresponding transmission values obtained. Light transmission of the radiograph was directly related to calcification level. The difference in these transmission values was established, and the per cent difference was derived. These differences, at the various time intervals, were compared (Figure 9) and recorded (Table I), to demonstrate changes in calcification. In this report, the terms calcification, mineralization, and sclerosis will be used interchangeably.

Linear Measurement Instrumentation and Procedures (Figure 11)

An illuminated, adjustable marker dot and a selected line of scan, along which it moved, were generated by a second oscilloscope. This measuring probe was set at the desired point from which measurement was to begin, and the digital readout device was offset to read zero. As the marker dot moved away from zero, the distance traveled was electronically registered. The instrumentation was calibrated to accurately

measure distances, in hundredths of millimeters, throughout the television image. Each radiograph was rotated in the Optoliner so that the horizontal television line of scan would pass through the bifurcation and the area of the pulpal floor to be measured. In each instance, the measuring probe was zeroed at the bifurcation and moved horizontally until the desired boundary - the pulp chamber roof or cavity floor - was reached. The intervening distances were recorded from the image of the digital display unit. Information regarding pulpal floor thickness, secondary dentin deposition, and amount of residual caries was derived and further evaluated, as described in Figure 11 and recorded in Table I. The terms secondary dentin and reparative dentin are considered synonymous in this paper.

DATA

To quantitatively evaluate the rate and amount of calcification and secondary dentin deposition following indirect pulp capping, the 45 teeth, which did not demonstrate evidence of irreversible pulpal degeneration or pulpal exposure, from the original sample of 50 were divided into two groups (Table I) on the basis of the total thickness of the pulpal floor beneath the calcium hydroxide medication. Group I included 21 teeth with thin pulpal floors, all less than a total thickness of 1000 microns of carious and sound dentin. The average thickness of sound dentin was 223.8 microns. Group II included those with thicker floors, all exceeding a total thickness of 1000 microns. The mean thickness of sound dentin in the pulpal floors of these 24 teeth was 1049.0 microns. Similar amounts of residual caries were removed from each group at the final appointment, 456.7 microns from Group I lesions and 563.5 microns from Group II teeth. In considering the data, it is important to point out that, in all instances, the one-year sample was limited to 18 of 45 teeth.

Figure 12 compares accumulated secondary dentin thickness and the mean calcification levels of the underlying dentin beneath the calcium hydroxide-treated carious dentin, with respect to time. These mean calcification level values were derived from the periodic per cent differences of the sample area from the control, which was regarded as stable throughout the study. Periodic variations in these calcification differences

were recorded as changes in calcification level. After one month, the calcification level, as measured electronically, of the treated dentin increased by 10.9 per cent. At the three month recall, it had demonstrated a dramatic decrease to 2.9 per cent above the preoperative level. Subsequently, calcification increased to 9.5 per cent at six months, 17.5 at nine months, and 38.1 at one year. After one month of treatment, the average pulpal floor received 98.7 microns of new reparative dentin. The accumulation increased to 191.6 at three months, 266.3 at six months, 330.5 at nine months, and 376.6 at one year.

Figure 13 shows the influence of pulpal floor thickness on the deposition of secondary dentin. Initially, the teeth in Groups I and II demonstrated nearly identical amounts of secondary dentin formation. After six months, the thinner pulpal floors of Group I had accumulated 272.8 microns of new dentin, while those of Group II had demonstrated slightly less, 260.5 microns. At nine months, the difference had increased to 40 microns. After one year, Group I teeth had accumulated 397.4 microns and Group II teeth 358.5 microns of new dentin.

The influence of pulpal floor thickness on changes in calcification level are shown in Figure 14. One month after treatment, calcification increased in Group I by 5.8 per cent and in Group II by 15.2 per cent. At three months, Group II

showed a loss of calcification to 6.4 per cent. The dentin of thinner pulpal floors experienced decreases to -1.1 per cent below the preoperative level. By six months, calcification had again increased to 0.6 per cent for Group I and 17.1 for Group II. At nine and 12 months, Group I teeth increased their calcification to 8.5 and 22.9 per cent, while Group II teeth, with their greater amount of calcification, continued to 25.3 then 52.5 per cent above the preoperative level.

Figure 15 compares the rates of activity of calcification, in per cent per month, and of secondary dentin, in microns per day, relative to elapsed time. This data was calculated from the increments of activity between each recall appointment, as derived from Table I. During the first month, reparative dentin was deposited at the rate of 3.3 microns per day. Throughout the study, the level of activity decreased steadily to 1.55 microns per day during the following two months, 0.83 between three and six months, 0.71 during the next three months, and finally to a mean rate of 0.51 microns per day between the ninth and twelfth months. Similarly, the rate of calcification was highest during the first month, at 10.9 per cent per month. During the second and third months, calcification was depleted at a mean rate of 4.0 per cent per month. Between three and six months, an increase in calcification began to recur at 2.2 per cent per month. A very slightly increased rate of 2.7 was seen during the next 90 days, followed

by a more accelerated rate of 6.9 between nine and 12 months.

The manner in which the pulpal floor thickness influenced the rate of secondary dentin deposition is illustrated by a graph, Figure 16. During the first month, similar rates of 3.25 and 3.32 microns per day were seen for Group I and Group II. During the following two months, the rates were 1.58 and 1.52. During the second three-month period, teeth with thinner floors experienced a somewhat higher rate of activity, 0.89, compared with 0.77 microns per day for Group II teeth. This rate advantage for Group I persisted between the sixth and ninth month, 0.88 to 0.57 microns per day. During the last three months of the study, the rates were almost identical. Group I deposited 0.51 microns per day, as compared to 0.52 for Group II.

Figure 17 illustrates how the rate of calcification, in per cent per month, was influenced by pulpal floor thickness. The highest rate of calcification activity occurred during the first month. Those teeth with thicker floors experienced a considerably higher rate, 15.2 per cent per month, than did those with deeper carious lesions, at 4.4 per cent per month change. Whereas, Group I calcification rates steadily climbed during the following three three-month periods, 0.6, 2.6, and 4.8 per cent per day, the rates for Group II rose to 3.6, dropped again to 2.7, and finally rose to a 9.1 per cent per month rate of calcification activity.

A bar graph (Figure 18) shows how reparative dentin deposition effects a per cent increase relative to the original preoperative thickness of the sound pulpal floor. At one month, thin pulpal floors experience an increase in thickness of 43.6 per cent, as compared to only 9.5 per cent increase for Group II cases. Group I steadily increases to 85.9 at three months, 121.9 at six months, 157.2 at nine months, and finally to 177.6 per cent of the initial sound pulpal floor width, at one year. Group II floor thicknesses also continue their increases, although less dramatically, to 18.2 at three months, 24.8 at six months, 29.7 at nine months, and 34.2 at one year.

ILLUSTRATIONS

Figure 1. A typical tooth with a deep carious lesion selected for this study.

- A. The preoperative clinical condition of the tooth.
- B. A preoperative radiograph using the individual film holder.

Figure 2. Clinical preparation of the deep carious lesion for study in this investigation.

- A. The superficial, necrotic layer of caries has been removed. The barium sulphate radiographic indicator has been placed across the cavity floor.
- B. A typical study radiograph clearly defines the pulpal floor (PF) of the cavity preparation, the roof (R) of the pulp chamber, and the bifurcation (B).

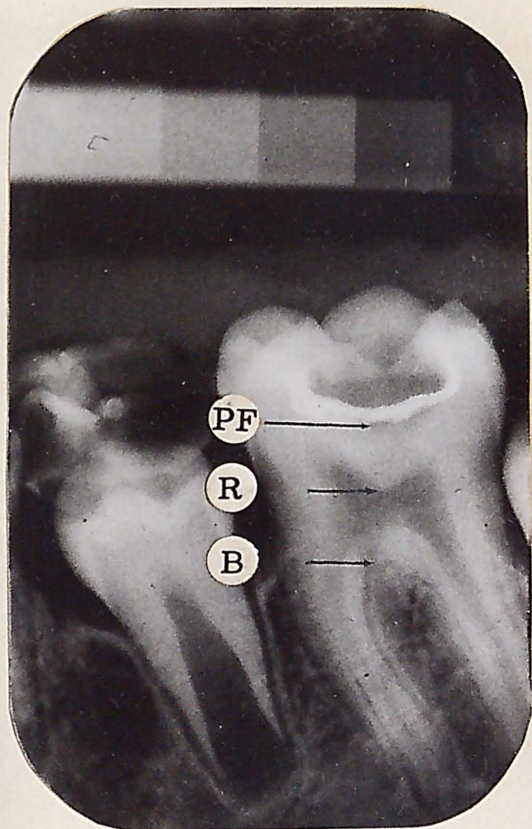
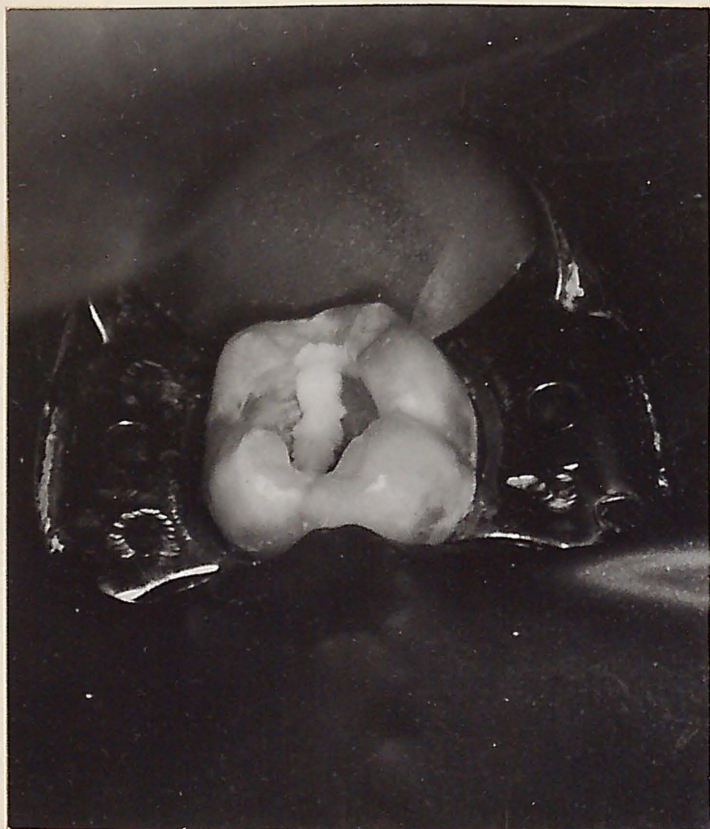


Figure 3. The components used for obtaining the serial radiographs.

- A. X-ray control unit
- B. Head of x-ray tube
- C. Metal cone
- D. Constant-distance rod
- E. Individual film holder

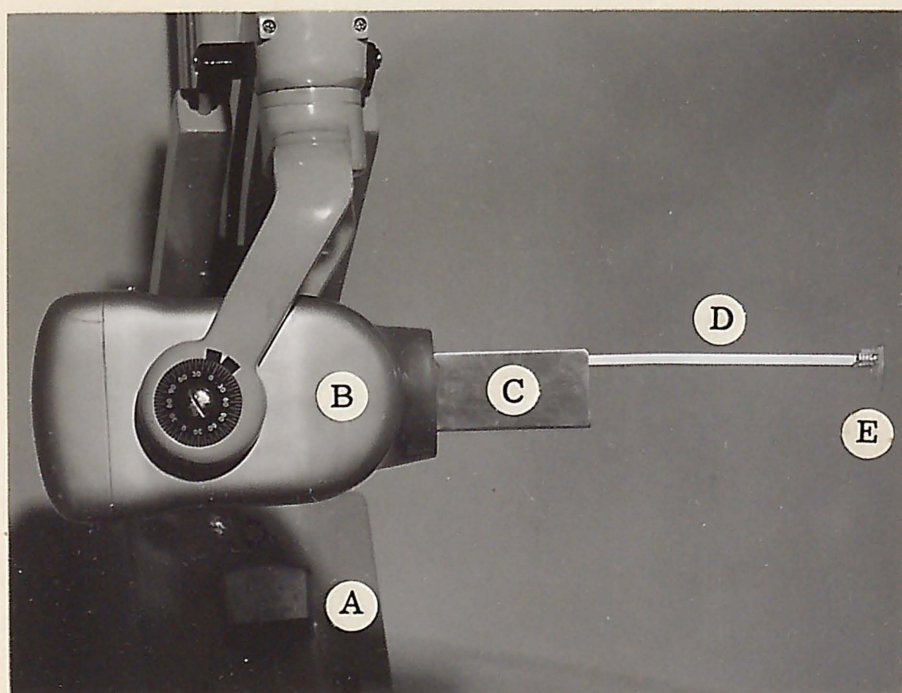
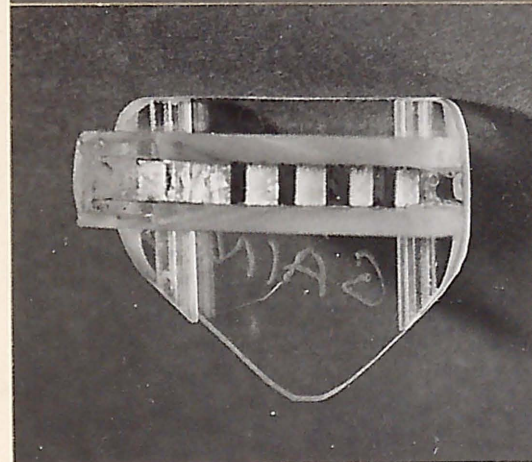
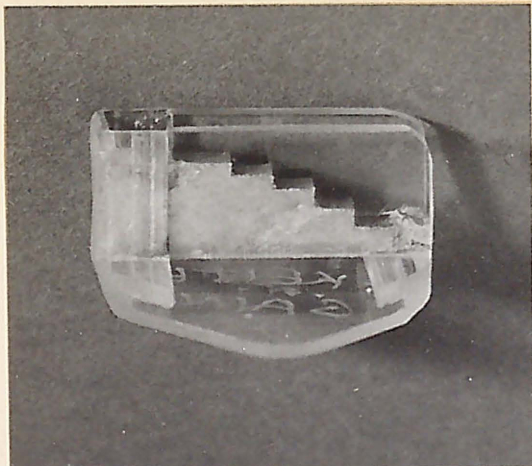


Figure 4. The individual acrylic film holder with its standardized aluminum step-wedge. The steps are numbered from one to five, beginning from the rod support assembly at the anterior aspect.

Figure 5. The individual film holder prepared for clinical use. The compound bite index is supported by the step-wedge housing and the distance-rod support assembly. The Type 0 film is in place within its retention slots.



All dimensions in (mm)

9 4 4 4 4

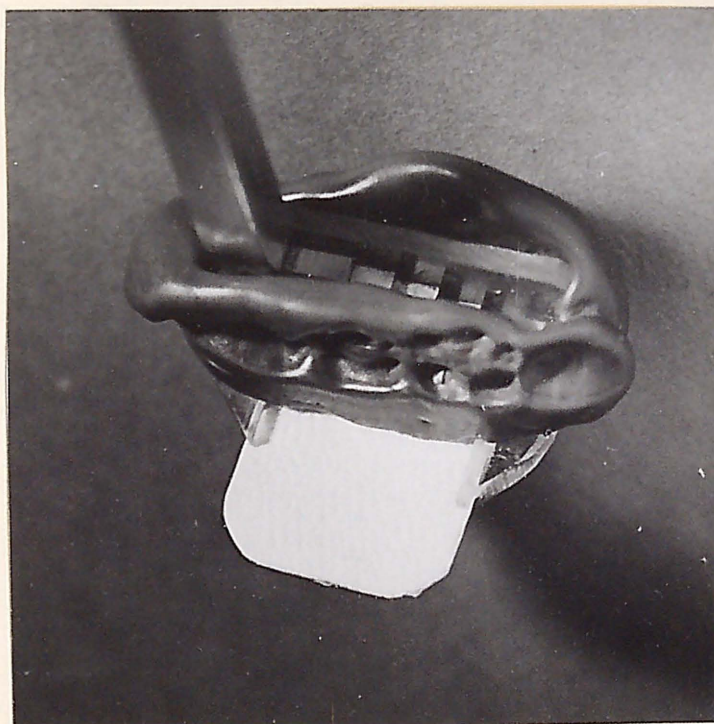
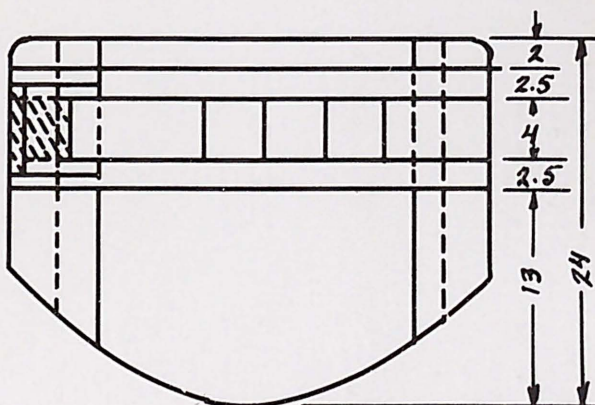
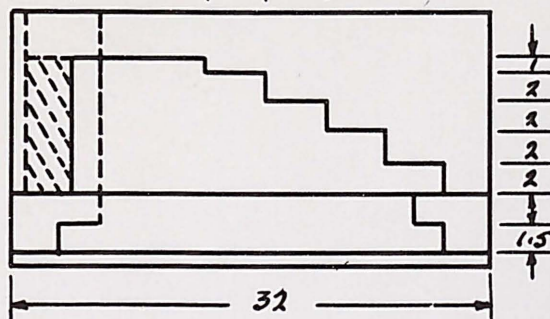


Figure 6. Clinical application of the film holder.
The film holder is coupled to the constant-
distance rod and maintained in position by
intermaxillary pressure.

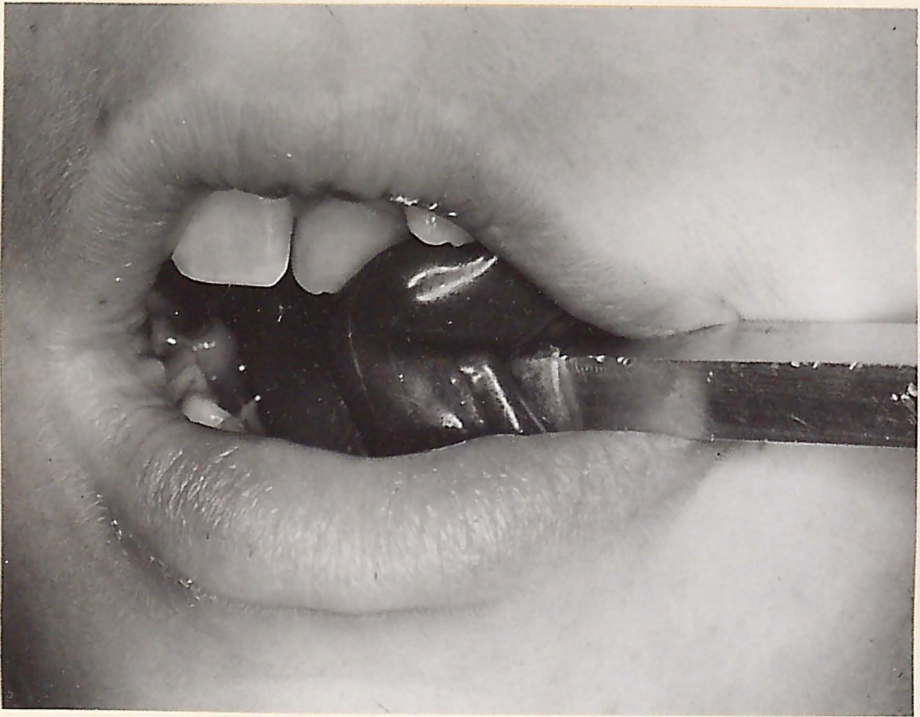


Figure 7. The instrumentation used for density and linear measurements in the Television Research Laboratory of Indiana University School of Dentistry.

- A. Television Optoliners and associated television cameras.
- B. Digital readout unit and associated television camera.
- C. MacBeth Quanta-Log.
- D. Oscilloscope used for selection of areas to be investigated. Its waveform also helps monitor the scan line being observed.
- E. Master monitor. For clinical observations and indications of areas to be measured.

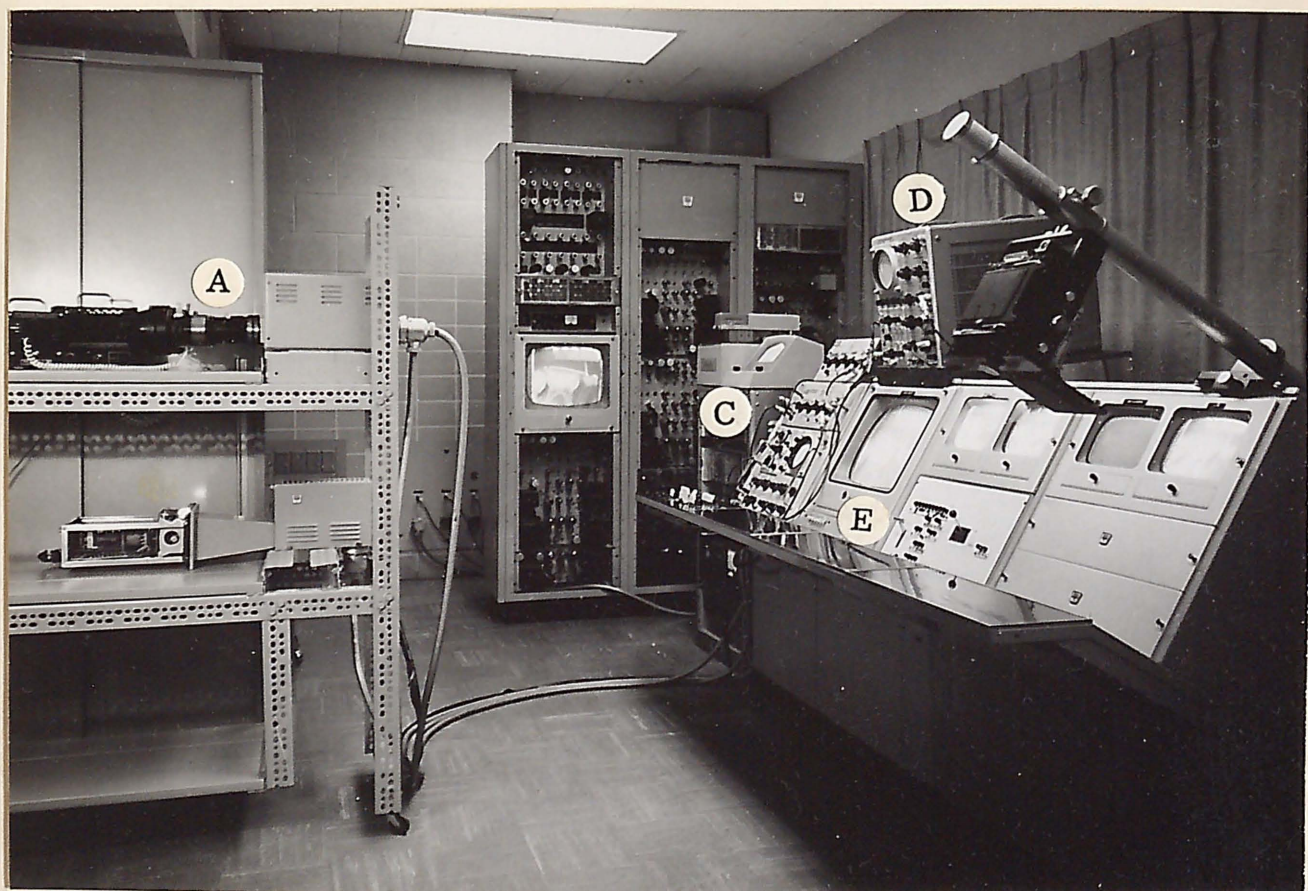


Figure 8. Schematic block diagram of television densitometric and linear instrumentation. This illustrates the electronic pathways and intervening components required to perform the quantitative radiographic evaluations.

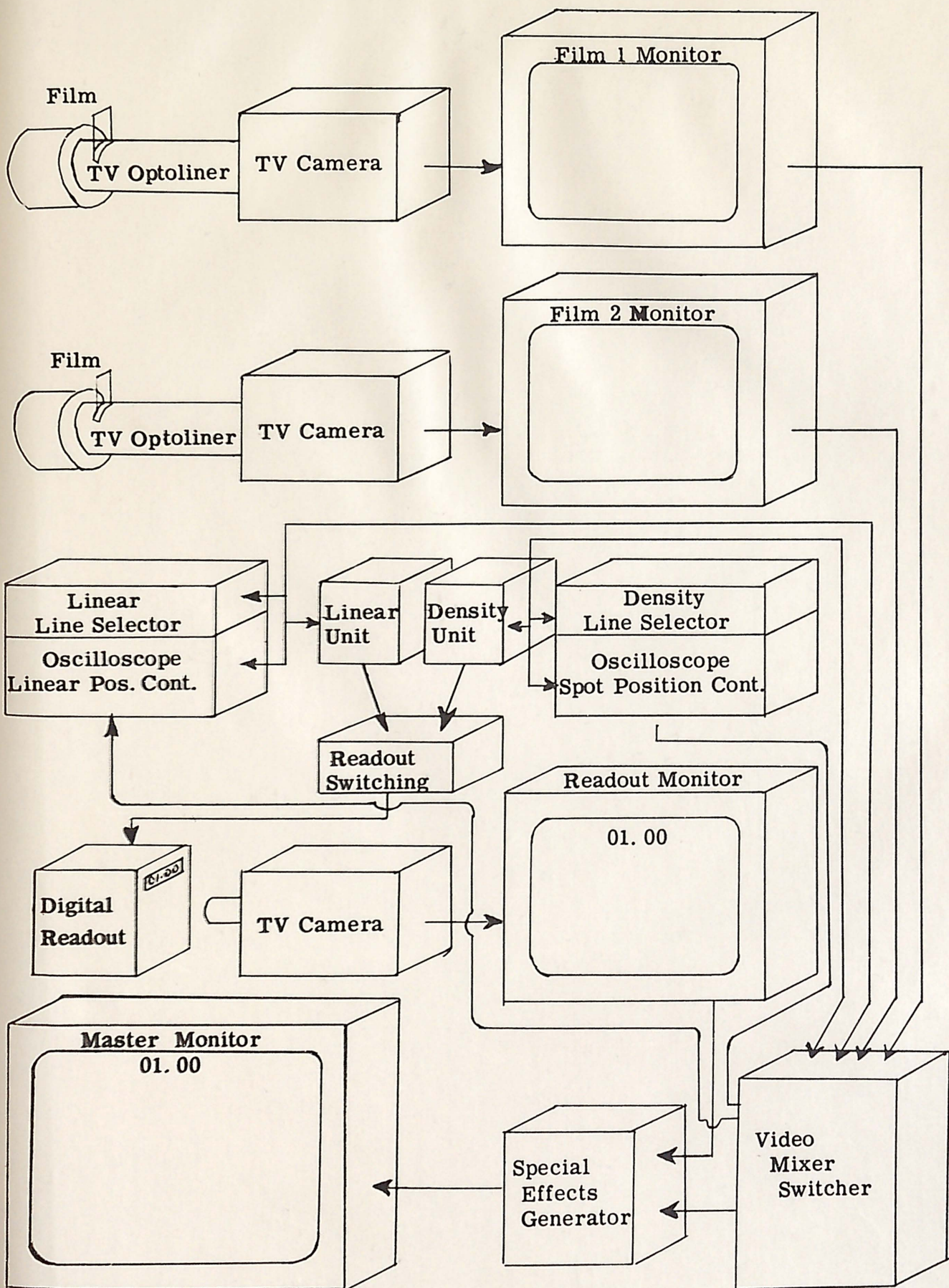


Figure 9. Television densitometric measurement of serial radiographs, photographed from the master monitor.

- A. Preoperative film showing degree of carious involvement.
- B. First appointment. The superficial caries has been removed and the barium sulphate indicator placed for linear measurements. After calibrating the television instruments with the step-wedge, a sample (S) and control (C) area is selected for density measurement. The density values from the digital readout unit are displayed on the screen. Using the density conversion chart to adapt to the density range of the specific film, the per cent difference (P_0) of the sample area density (D_s), or calcification, from the control density (D_c), is calculated:
- $$\frac{D_{s_0} - D_{c_0}}{D_{s_0}} \times 100 = P_0$$
- C. One month radiograph. The television amplifier range is again adjusted to the density range of the new radiograph. The control and sample areas are again measured. The per cent difference (P_1) between the sample and control densities are calculated. The actual change in calcification ($P_1 - P_0$), relative to the preoperative film, reflects an increase of 15 per cent.
- D. Three month radiograph. A loss of calcification to 11.9 per cent ($P_3 - P_0$) above the preoperative level was recorded.
- E. Six month radiograph. A considerable increase in sclerosis has occurred. The calcification level is a 32 per cent ($P_6 - P_0$) above the first appointment.
- F. Nine month radiograph. The amount of sclerosis is virtually unchanged.
- G. One year radiograph. The remaining caries has been removed. An atypical drop in calcification has occurred to 29.1 per cent ($P_{12} - P_0$) above the first appointment measurement. Concurrently, 310 microns of secondary dentin has been formed.

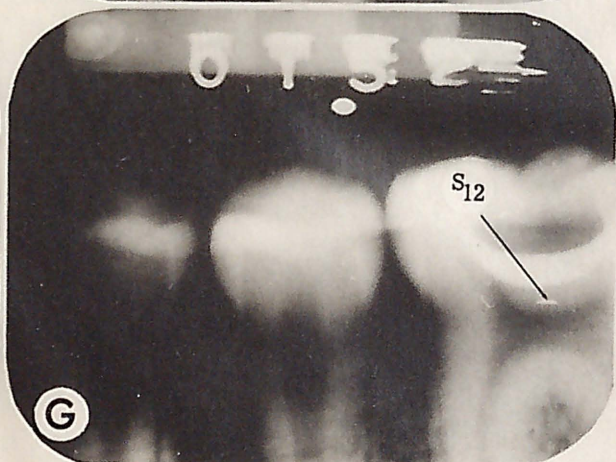
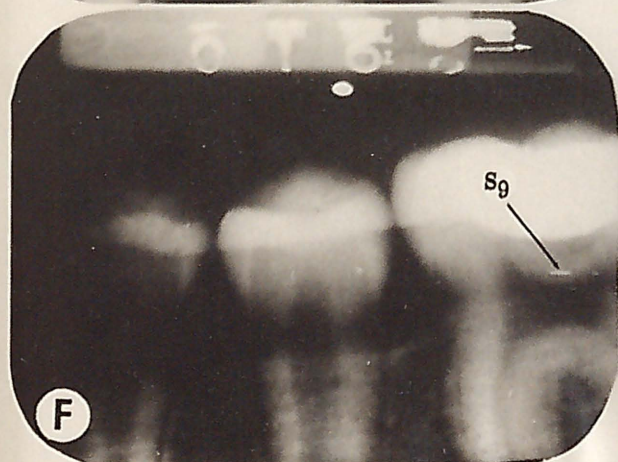
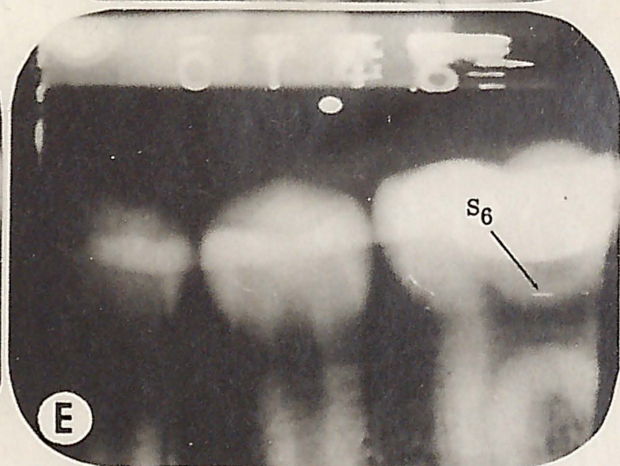
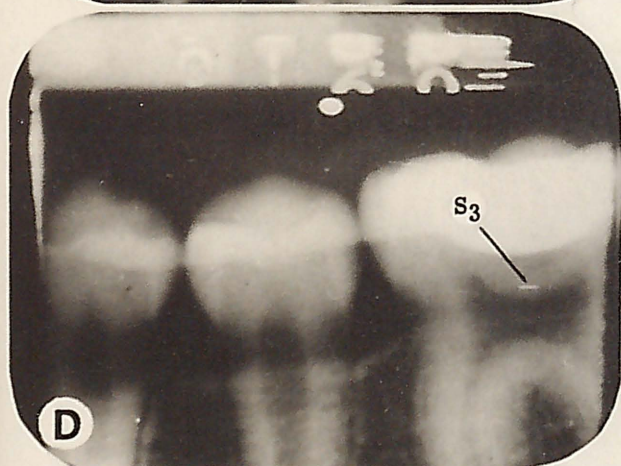
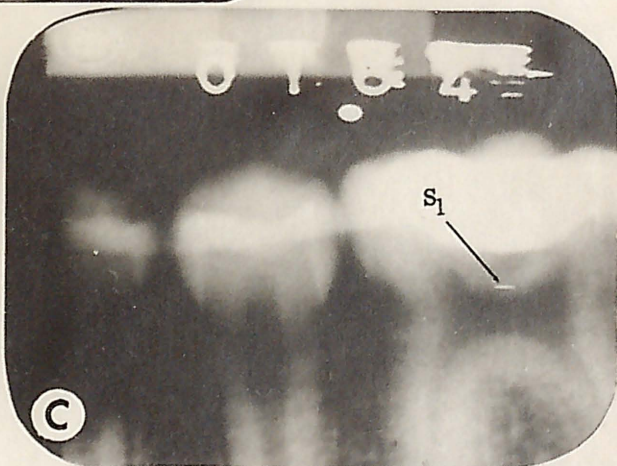
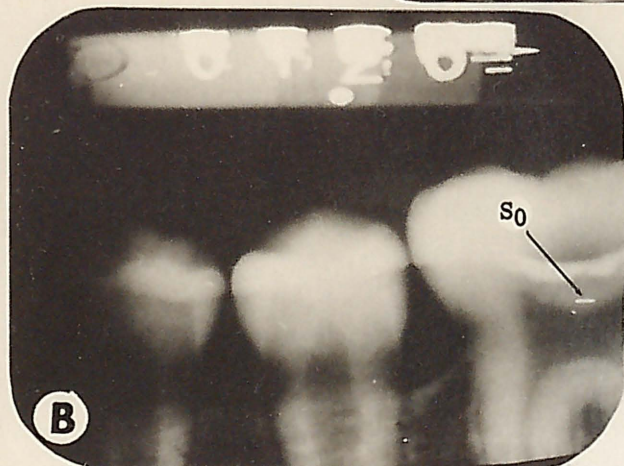
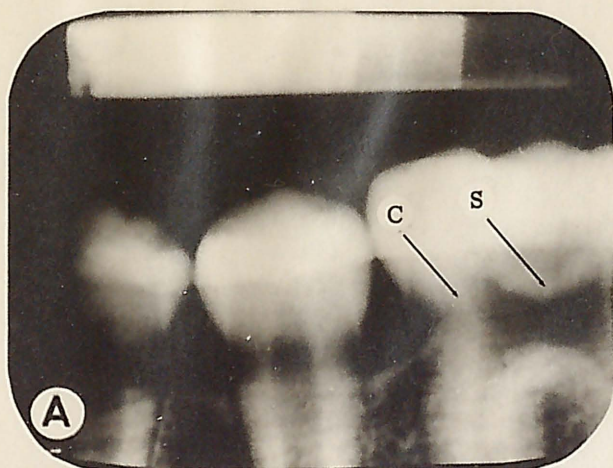


Figure 10. The density conversion chart. This was derived from a standard density-opacity-transmission table and adapted to the average densities of steps two and four of the step-wedges in this study. This chart adapted to the various density ranges of individual films and permitted more accurate determinations of their light transmission values. Light transmission of the films directly related to degree of calcification.

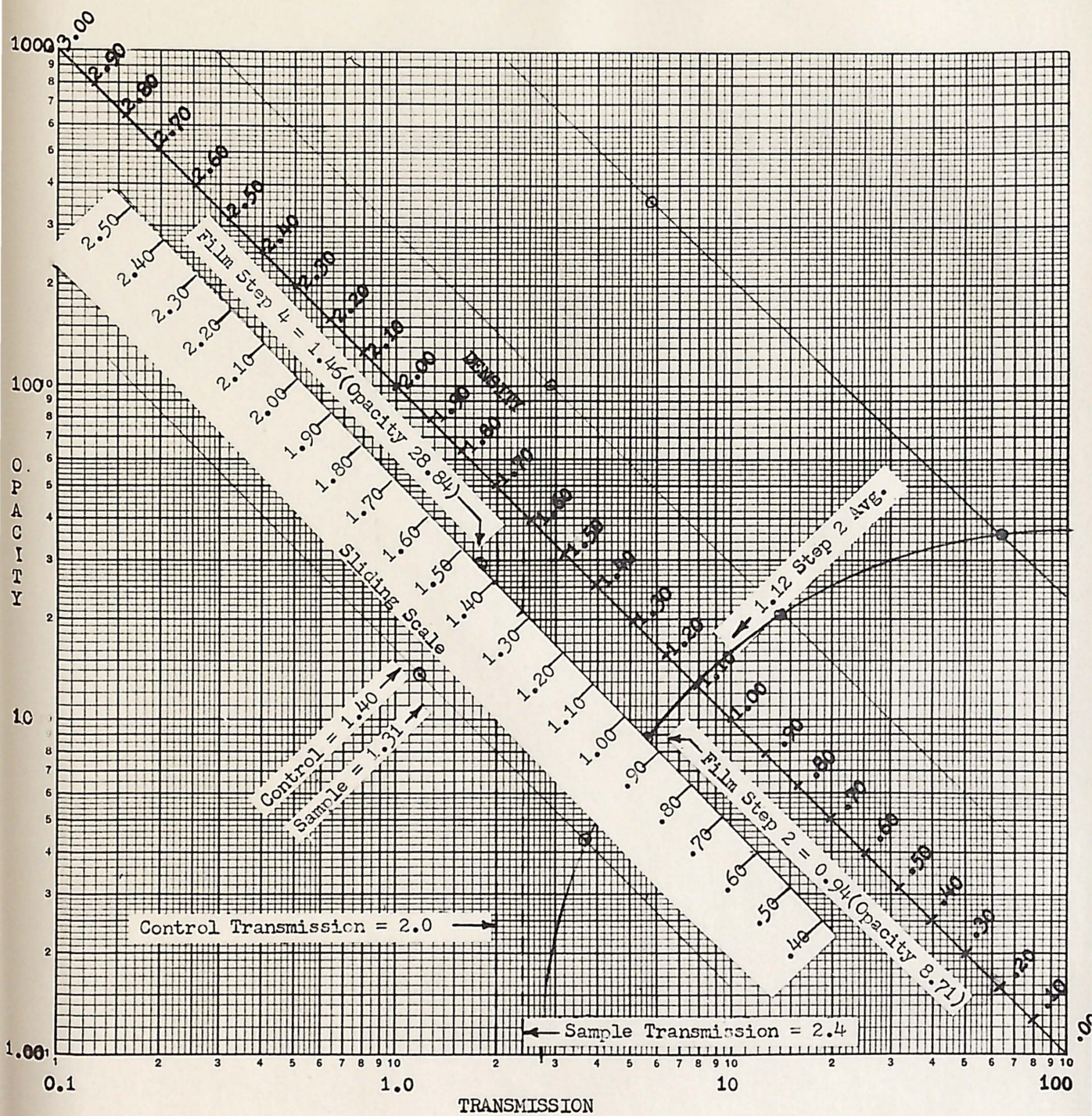


Figure 11. Photographs of master monitor demonstrating television linear measurement of serial radiographs.

- A. Preoperative film showing degree of carious involvement. This Group I tooth had an initial sound pulpal floor thickness of 290 microns.
- B. First appointment. The radiograph is rotated to coincide with the horizontal scan line of measurement. The distance (BPF_0) is measured from the bifurcation (b) to the barium sulphate indicator on the pulpal floor (PF_0) on the cavity preparation.
- C. First appointment. The distance (BR_0) from the bifurcation (B) to the roof (R_0) of the pulp chamber is measured. The medication distance (M_0) from the pulp is found to be 770 microns ($BPF_0 - BR_0$).
- D. One month. After measuring the new, decreased distance (B) to (R_1), we find that 250 microns ($BR_0 - BR_1$) of reparative dentin has been formed on the roof of the pulp chamber.
- E. Three months. Calculations ($BR_0 - BR_3$) show that a total of 320 microns of new dentin has accumulated.
- F. Six months. ($BR_0 - BR_6$) reveals that 560 microns have been deposited since the beginning of treatment.
- G. Nine months. At the last appointment, all residual caries has been removed and the barium sulphate indicator placed on the floor of the cavity. Reparative dentin has increased in thickness to 680 microns ($BR_0 - BR_9$).
- H. Nine months. The distance (BPF_2) to the "new" pulpal floor was electronically measured. Calculations ($BPF_0 - BPF_9$) showed that the thickness of the residual caries (C), was 480 microns. The original thickness of sound dentin on the pulpal floor ($M_0 - C$) was 290 microns. Calcification increased 40 per cent. The adjacent deciduous second molar gained 200 microns of new dentin and increased in calcification by 90 per cent.

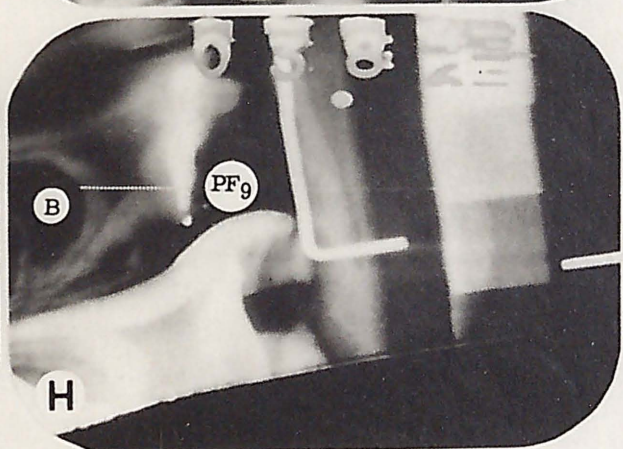
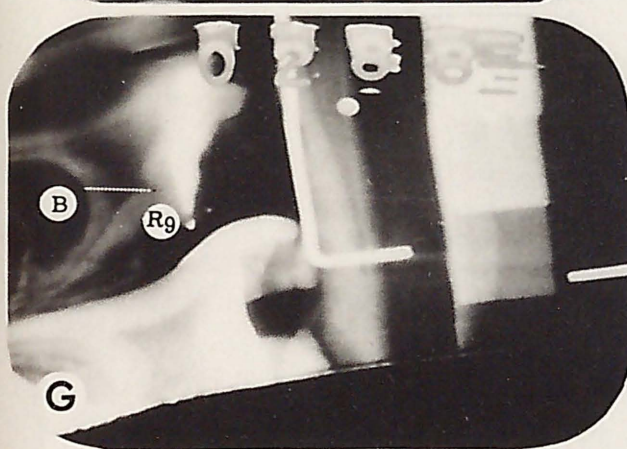
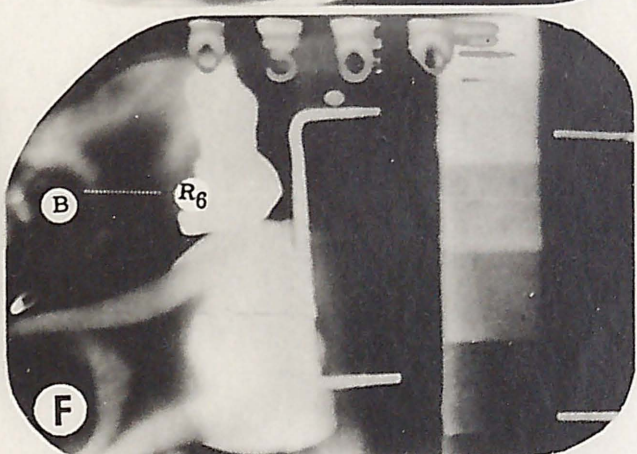
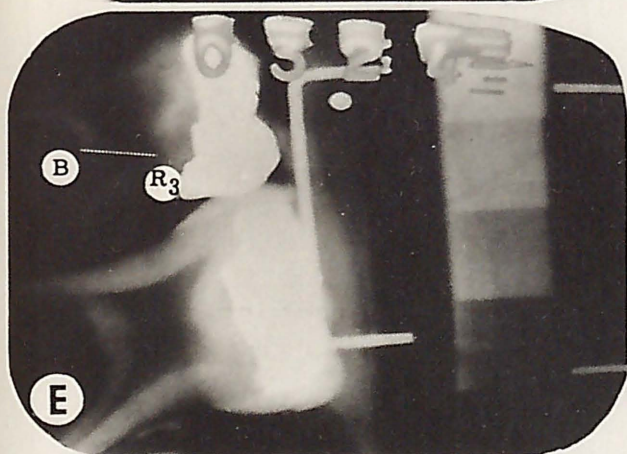
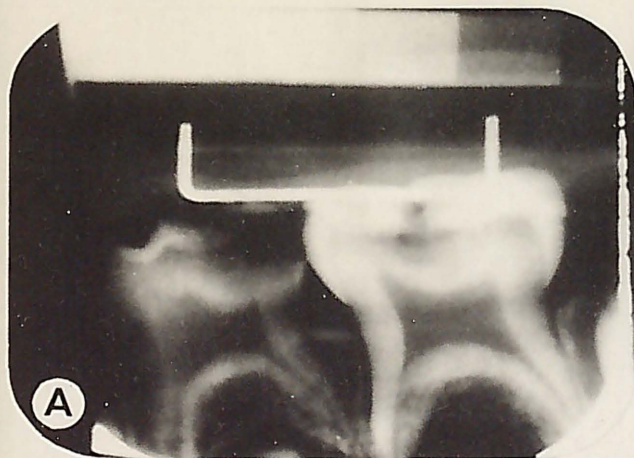


Table I. Mean medication distances, secondary dentin thicknesses, and calcification levels. From this data, comparisons were made of differences in physiologic responses to treatment between Group I and Group II teeth. The distance of the calcium hydroxide - methyl cellulose from the pulp was less than 1000 microns for Group I and in excess of 1000 microns for Group II teeth.

MEAN MEDICATION DISTANCES, SECONDARY DENTIN
THICKNESSES, AND CALCIFICATION LEVELS

	NO. TEETH	MEDICATION DISTANCE FROM PULP (MICRONS)			SECONDARY DENTIN THICKNESS (MICRONS)					CALCIFICATION LEVEL (% OF CONTROL)				
			CARIES THICK.	SOUND PULP. FLOOR	TIME (MONTHS)					TIME (MONTHS)				
					1	3	6	9	12	1	3	6	9	12
GROUP I (thin pulpal floor)	21	680.5	456.7	223.8	97.6	192.3	272.8	351.8	397.4 [*]	5.8	-1.1	0.6	8.5	22.9 [*]
GROUP II (thick pulpal floor)	24	1612.5	563.5	1049.0	99.6	190.9	260.5	311.8	358.5 ^{**}	15.2	6.4	17.1	25.3	52.5 ^{**}

^{*} GROUP I 12-month sample limited
to nine teeth

^{**} GROUP II 12-month sample limited
to nine teeth

Figure 12. Comparison of average changes in calcification level and secondary dentin thickness with time. This graph depicts how, in an average case, secondary dentin thickness accumulates and calcification eventually increases in a cyclical pattern of activity.

COMPARISON OF AVERAGE CHANGES IN CALCIFICATION
LEVEL AND SECONDARY DENTIN THICKNESS WITH TIME

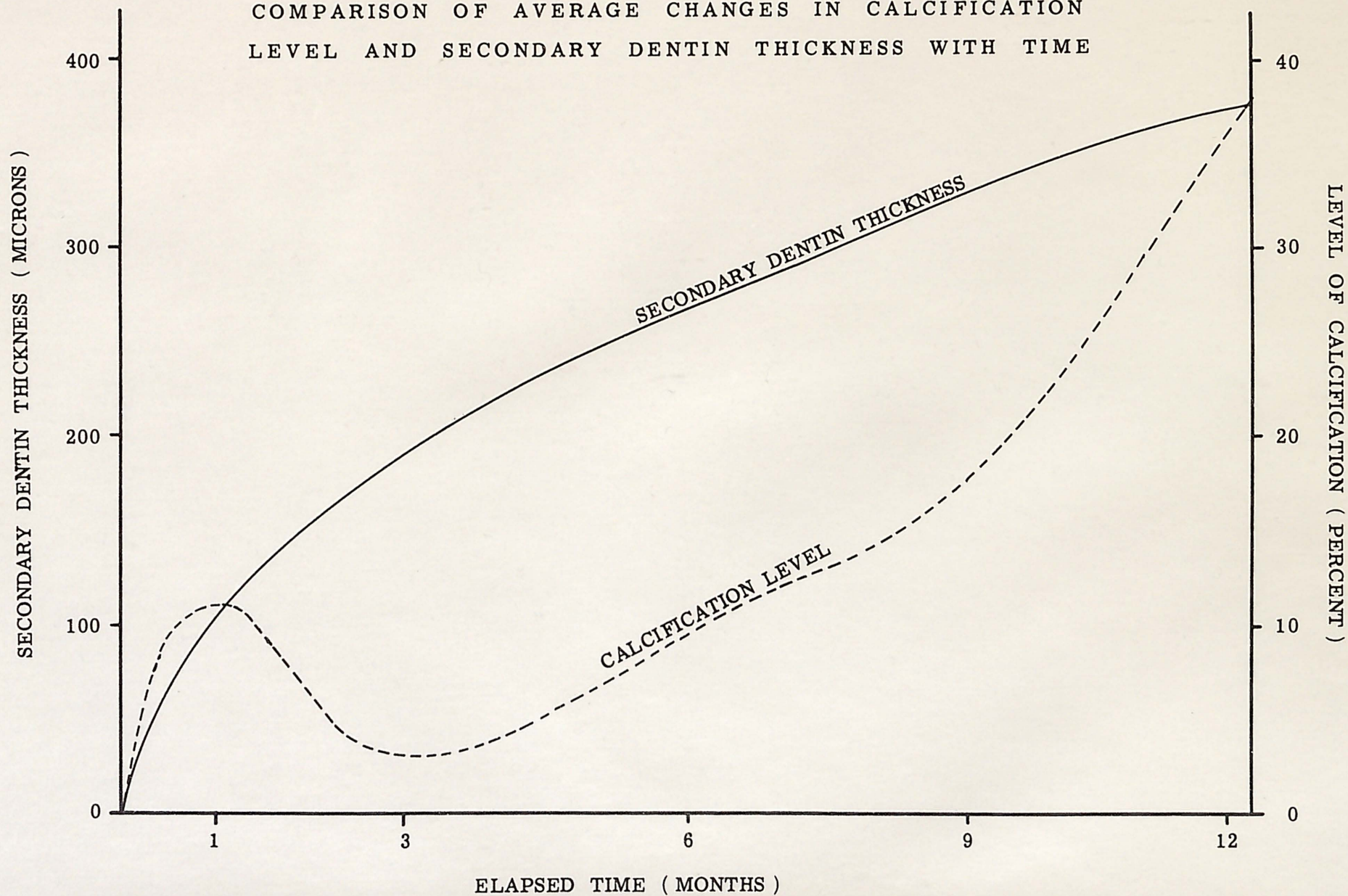


Figure 13. Influence of pulpal floor thickness on secondary dentin deposition. Thin and thick pulpal floors accumulate similar amounts of secondary dentin, but Group I teeth form slightly more with passage of time.

Figure 14. Influence of pulpal floor thickness on change in calcification level. Those teeth with thicker pulpal floors increased in calcification level to a greater extent than did those of Group I. A reliable level increase did not occur in Group I until approximately nine months postoperatively.

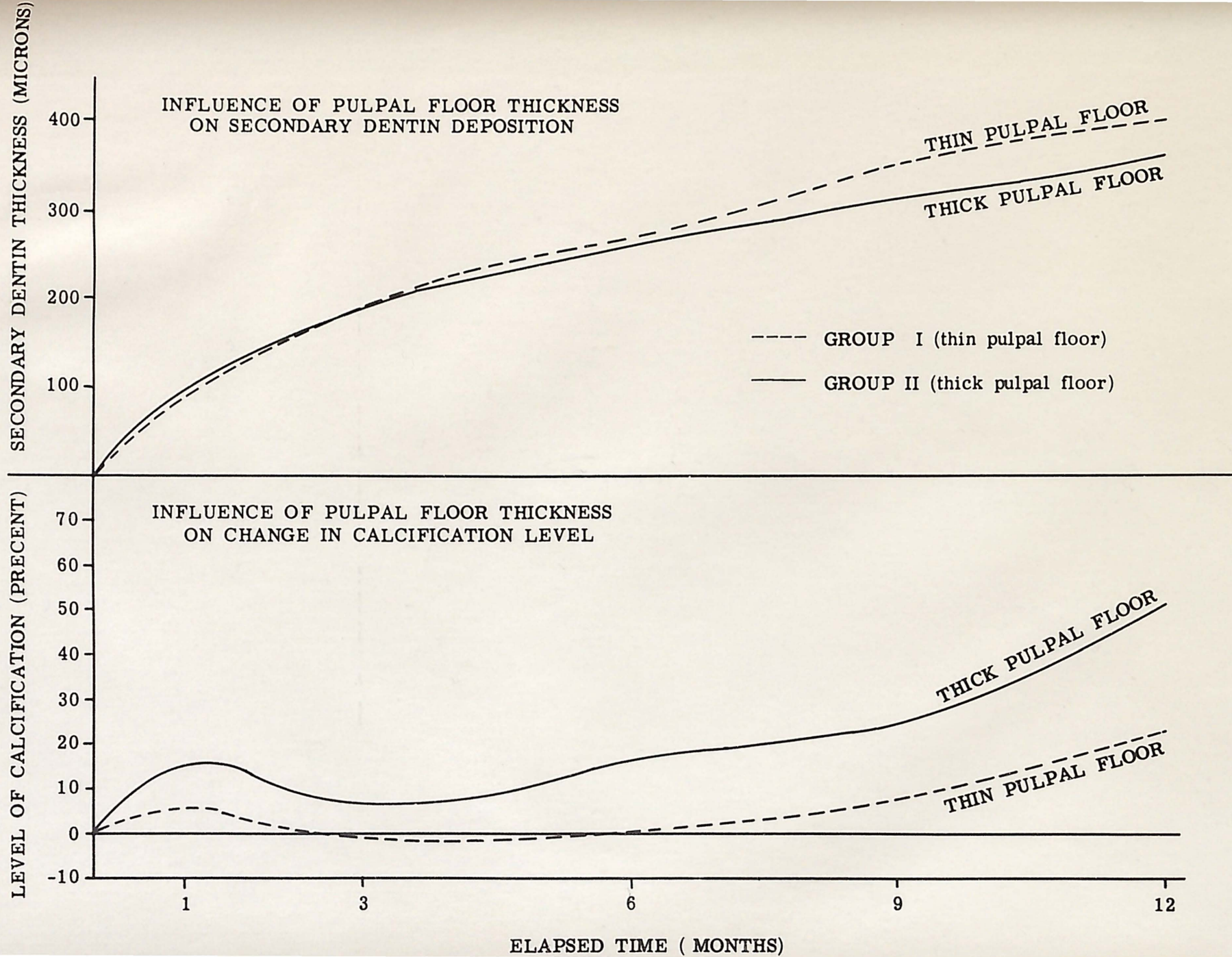


Figure 15. Comparison of average rates of change in calcification and secondary dentin. The mean rates of activity of the two processes are compared. The negative rate of calcification, following the initial high rate, indicates an actual, temporary depletion of mineral content from the underlying dentin. After maximum activity during the first month, the rate of reparative dentin deposition decreases steadily with time.

COMPARISON OF AVERAGE RATES OF CHANGE
IN CALCIFICATION AND SECONDARY DENTIN

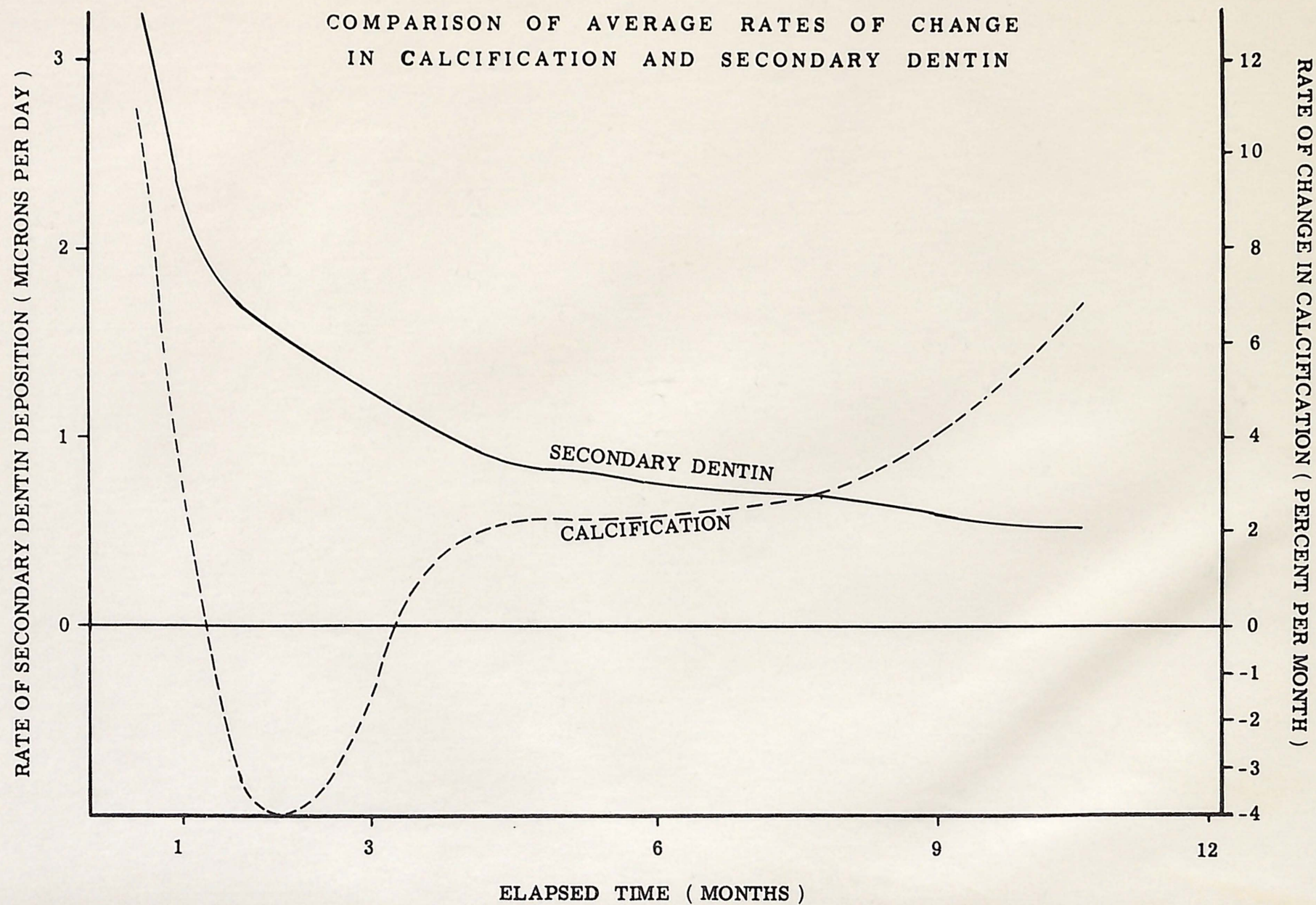
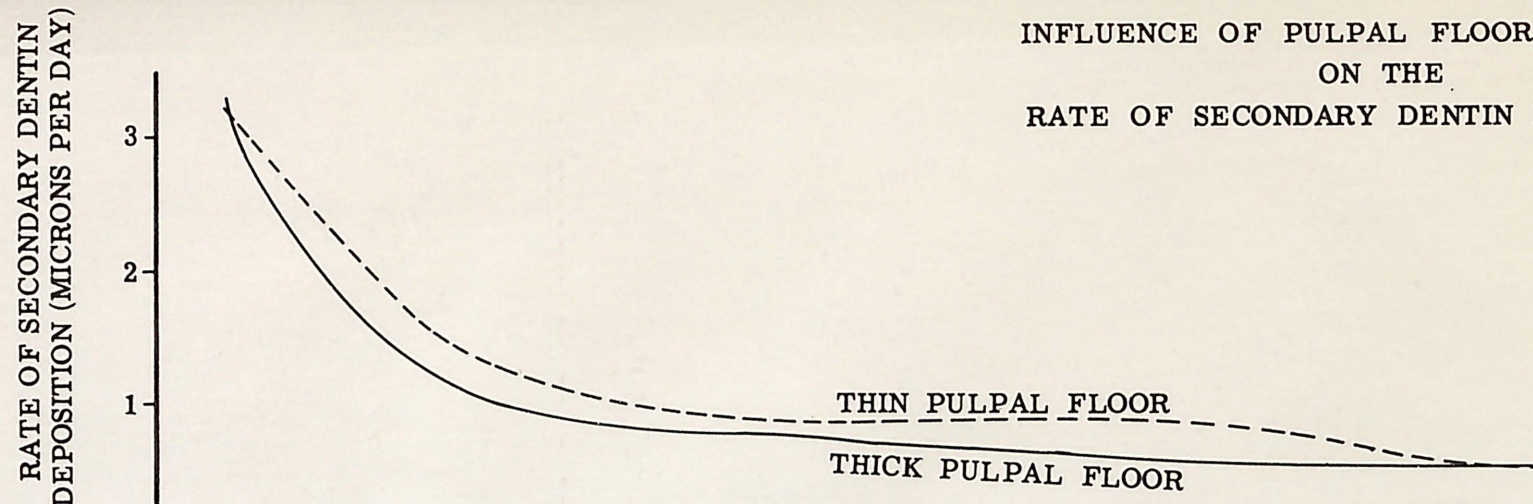


Figure 16. Influence of pulpal floor thickness on the rate of secondary dentin deposition. The rates below the pulpal floors of Group I and Group II are similar. Through most of the study, those teeth with thinner pulpal floors experienced a slightly higher rate of activity.

Figure 17. Influence of pulpal floor thickness on the rate of calcification change. The cyclical change, or "exchange" of mineral content is reflected in the rates of activity. The activity of Group II is generally greater. It tends to experience a second decrease in rate, or second cycle, while the rate of Group I steadily increases, after the characteristic initial rise and descent of activity.

INFLUENCE OF PULPAL FLOOR THICKNESS
ON THE
RATE OF SECONDARY DENTIN DEPOSITION



INFLUENCE OF PULPAL FLOOR THICKNESS
ON THE
RATE OF CALCIFICATION CHANGE

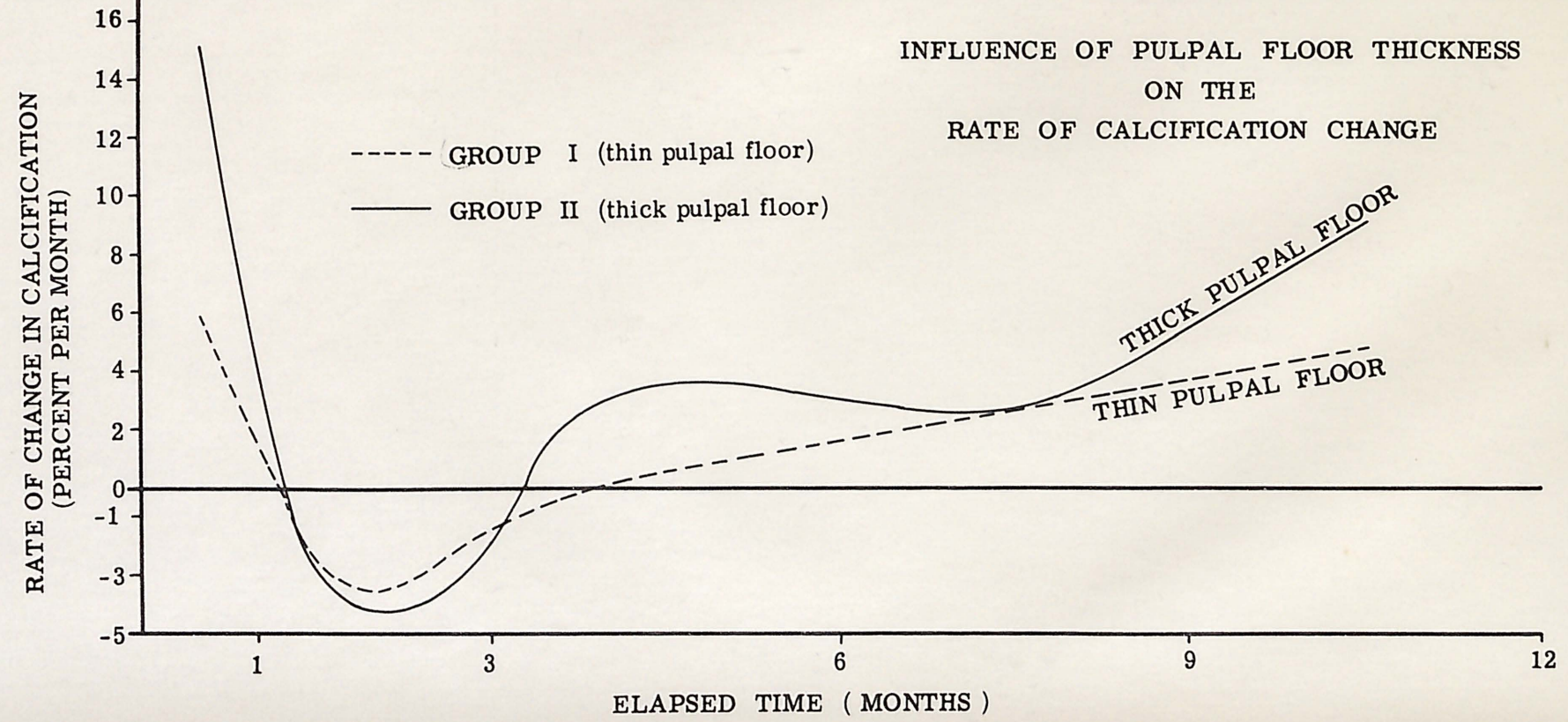
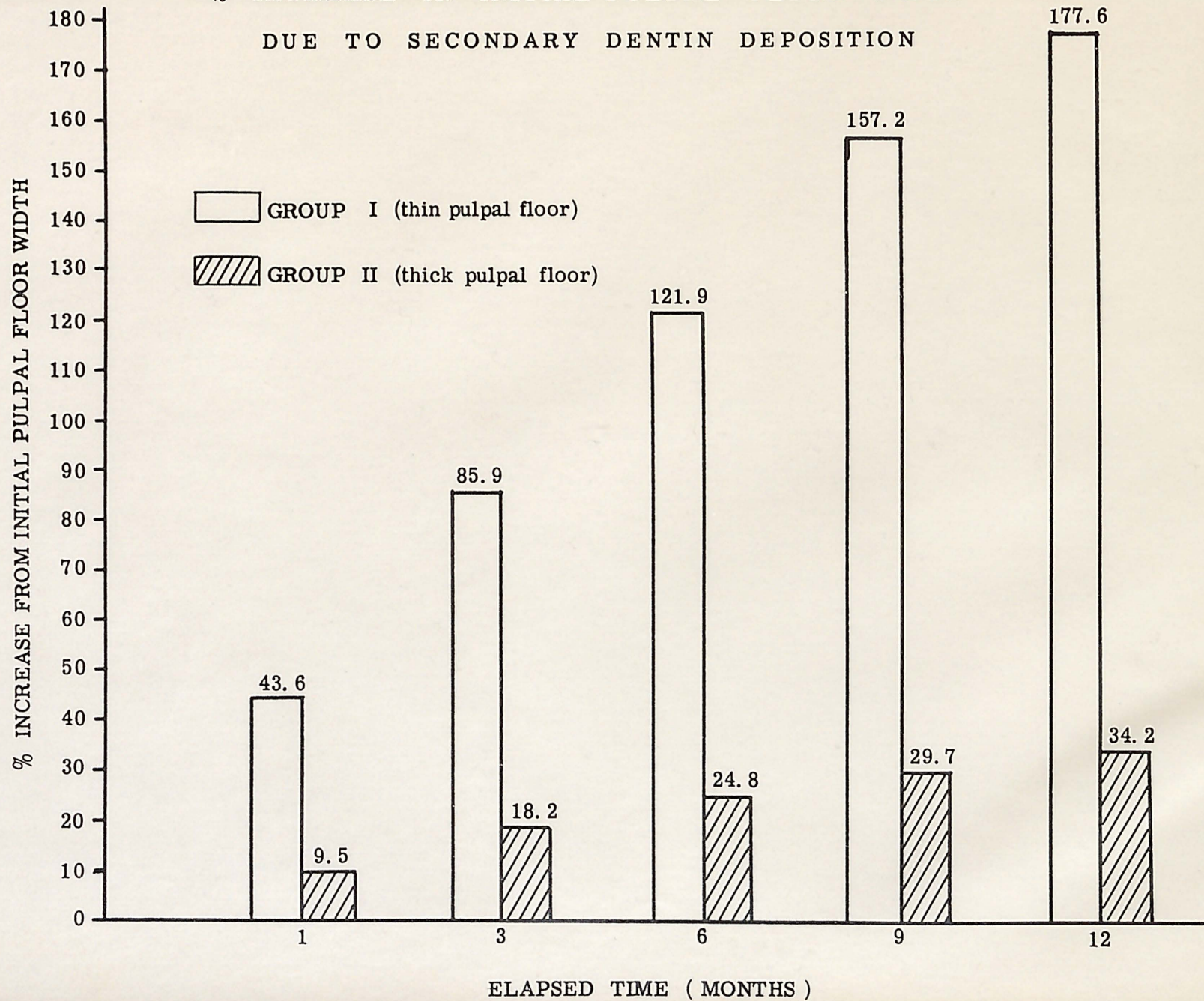


Figure 18. Per cent increase in initial pulpal floor width due to secondary dentin deposition. Group I and Group II teeth deposit nearly the same amounts of reparative dentin. However, the accumulated per cent increase in pulpal floor thickness, relative to the preoperative level, is dramatically greater for those with deeper carious lesions.

% INCREASE IN INITIAL PULPAL FLOOR WIDTH
DUE TO SECONDARY DENTIN DEPOSITION



DISCUSSION

The purpose of this study was to quantitatively measure the rate and amount of calcification and secondary dentin deposition below deep cavities treated by calcium hydroxide - methyl cellulose indirect pulp capping.

The results of this study indicate that reparative dentin accumulates rapidly following treatment and continues to accumulate over a 12 month period at a diminishing rate. Concurrently, calcification experiences a cyclical change, or "exchange," with an initial increase in mineralization in underlying pulpal dentin. This is followed by an apparent loss of mineral content and a subsequent and continuing increase in the degree of calcification. This type of cyclical activity, with considerable individual variation in activity patterns, was noted in all but three teeth. Although similar amounts of secondary dentin formed in the teeth of Group I and Group II during the first six months following treatment, those with thinner pulpal floors seemed to retain a slightly higher rate of activity, and they accumulated slightly greater amounts toward the end of the study. In contrast, pulpal floors of greater thickness showed higher levels of calcification throughout the study. Following the characteristic initial increase in mineral content, calcification levels of the thinner floors of Group I tended to return to their original preoperative levels, or slightly below, before beginning a very regular rate of increase. The cyclical changes

in rate of calcification activity were more pronounced in Group II. The initial rate of change was twofold over Group I. The characteristic loss also occurred at a comparatively greater rate. A slight recession in activity once again between six and nine months suggested a second cycle of mineral exchange.

This data supports the radiographic densitometric reports of Klein^{101,102} and the results of microhardness tests and densitometric evaluations by Mjor¹⁰⁰ both of which, although not dealing with the indirect technique, offer quantitative evidence of increased dentin calcification following treatment of dentin with calcium hydroxide. Upon re-entry into the cavities at the final appointments, the softened, carious dentin almost always had changed to a drier, seemingly harder texture. It has yet to be shown that carious, partially demineralized dentin is capable of "recalcification."

The reports^{53,83,88,107} that relate increased amounts of secondary dentin deposition to deeper cavity preparations are not substantiated by this study. However, the quantitative histologic findings of Stanley, White, and McCray⁸⁹ more closely agree with this data. They agreed that the factor of remaining pulp floor thickness did not appear to greatly affect secondary dentin deposition, in their non-carious, prepared, unrestored teeth. They had measured an average rate of deposition of 1.4 microns per day through the 132 days

of their study. The data herein reflects, through 182 days, an average rate of 1.46 microns per day. The effect of the calcium hydroxide medication may account for the earlier initiation of reparative dentin formation and the generally greater rates of deposition in this study.

Of the 50 teeth initially charted for this study, five were considered failures and were not included in the quantitative evaluations. Three of these were frank clinical or radiographic failures, and the pulps of the other two were exposed at the final visit, when residual caries was removed. The rate of complete success, therefore, was 90 per cent.

It is interesting to note that, had all caries been excavated at the first sitting, the thickness of remaining sound dentin in 16, or 36 per cent, of the 45 teeth would have been 200 microns or less. This is probably a conservative figure, considering that radiographic images may not demonstrate the thinnest areas of the pulpal floors where undetected exposures or near exposures may exist. In seven of the teeth, the amount of caries removed at the last appointment exceeded the initial total pulpal floor thickness and would have resulted in exposures. The fact that thinner pulpal floors of Group I accumulated an average of 177 per cent increase in thickness reflects one reason why more pulp exposures were not encountered. Assuming for a moment that some "remineralization"

of affected dentin does occur, an even higher incidence of pulpal exposures than this study shows might have occurred, following initial complete caries removal, had not the indirect capping approach been employed.

It has been suggested^{18,49,70,76} that calcium hydroxide be allowed to react with dentin for six to eight weeks before re-entering for complete caries excavation. This study suggests that a reliable and significant increase in calcification level does not occur until six to nine months post-operatively, especially in very deep lesions. By this time, a 45 per cent average increase in width of the sound pulpal floor has occurred. There is justification for leaving the calcium hydroxide dressing and silver amalgam restoration in place for considerably longer than previously has been recommended, to benefit fully from the natural protective mechanisms.

A high degree of reproducibility of density measurements and linear dimensions, using identical instrumentation, was demonstrated by Convery,¹⁵³ in 1967. An element of error was introduced into this study by the variation in radiographic procedures. The dynamic nature of the ever-changing dentition of the child made accurate replacement of the compound occlusal index of the film holder questionable, at times. Lack of precise control in developing produced films with variation in both density and contrast. These variations

were greatest at the density range extremes. This precluded the possibility of comparing films directly. An attempt at correction of these problems was made by employing the density step-wedge to calibrate the television instrumentation to the individual films. The density conversion chart, which adapted to the various ranges, further minimized discrepancies. An unknown factor was the degree of possible change in calcification level of the selected control areas of dentin. Too, landmarks in some series were occasionally difficult to accurately relocate, from film to film. It should be repeated that the 12-month data was derived from a decreased sample of 18, due to time limitations imposed on this study. Subsequent investigations should attempt to utilize more stable film holders and carefully control the exposure and processing of radiographic films.

SUMMARY AND CONCLUSIONS

It was the purpose of this study to quantitatively measure the rate and amount of calcification and secondary dentin deposition below deep cavities treated by calcium hydroxide - methyl cellulose indirect pulp capping. Children aged three to 12 provided a sample of 50 posterior mandibular teeth with deep carious lesions. No clinical or radiographic signs of irreversible pulpal degeneration were apparent in 24 primary first molars, 16 primary second molars, nine permanent first molars, and a double-rooted first bicuspid.

Before beginning the operative procedure, the first of the identical, standardized serial radiographs was exposed. An individual acrylic film holder, which contained a density step-wedge, film retention slots, and a support assembly for the constant-distance rod, was held in a reproducible position by the patient's exertion of intermaxillary pressure on the compound bite index. The film holder was coupled to the head of the x-ray tube, in a stable relationship, by means of a fitted constant-distance rod and custom metal cone. Following the preoperative radiograph, the involved tooth was anesthetized and isolated with a rubber dam. The outline of the cavity preparation was formed with air-cooled, high speed rotary instruments. The remaining, superficial, necrotic layer of carious dentin was removed with spoon excavators and large round burs rotating at slow speeds. The deeper layer of caries which, if removed, might have exposed the dental pulp, was

allowed to remain. In the serial radiograph which followed removal of the rubber dam, the pulpal floor was identified by a water-soluble barium sulphate indicator paste. The rubber dam was replaced, the cavity was washed of barium sulphate, and a creamy mix of calcium hydroxide - methyl cellulose was placed on the cavity floor. The preparation was painted with Copalite and restored with silver amalgam.

Subsequent reproducible serial radiographs were exposed at one, three, six, nine, and, in some cases, 12 months post-operatively. At the final visit, the tooth was again anesthetized and isolated. Upon re-entry into the cavity, all residual caries was removed and observations made regarding the character of the pulpal floor texture and possible pulpal exposure. In the final serial radiograph, barium sulphate indicated the level of the "new" pulpal floor. Following replacement of the rubber dam, barium sulphate was thoroughly washed from the preparation. The tooth was restored with calcium hydroxide and silver amalgam, as before.

It was anticipated that each film would vary in density and contrast. A Quanta-Log densitometer gave density values for steps two and four of the standardized step-wedge in each film. The television density instrumentation then sampled each of the two steps as it was adjusted to the particular range. For each film, densities were measured for a chosen sample area within the treated dentin and a comparable

control area, which was assumed to remain stable throughout the study. Further compensation for radiographic variation was achieved by employing a density conversion chart. This graph arrangement adapted to the various density ranges to give more accurate measures of film transmission, or calcification level. Finally, the per cent difference of the sample density from the control density was determined, for each serial film. Changes in these differences occurring between recall appointments were related to the preoperative level and recorded as calcification changes.

The television linear measurement amplifier made it possible to accurately register distances, in hundredths of millimeters, between the bifurcation and either pulpal floor or pulp chamber roof. In this manner, information was calculated concerning pulpal floor thicknesses, secondary dentin deposition, and thicknesses of residual caries.

To evaluate the influence of pulpal floor thickness on the physiologic response to treatment, the sample of 45 teeth was divided into two groups on the basis of the total thickness of the pulpal floor beneath the calcium hydroxide medication. Group I included 21 teeth with thin pulpal floors, all less than a total thickness of 1000 microns. Group II included those with thicker floors, all exceeding 1000 microns. The average thickness of sound dentin within these floors was 223.8 microns, in Group I, and 1049 microns, in Group II.

The data indicates that secondary dentin accumulates rapidly following treatment and continues to accumulate at a steadily diminishing rate. Calcification shares a similar postoperative activity peak, followed by a characteristic loss of mineral content. An upswing in this cyclical change, or "exchange," is eventually re-established. Pulpal floor thickness has little effect of the amount of reparative dentin deposited, although thinner floors enjoy a slightly higher rate of activity and accumulate somewhat greater thicknesses of reparative dentin with the passage of time. Although Groups I and II add similar amounts of secondary dentin, the actual percentage of increase from the thickness of the initial sound pulpal floor is much more dramatic in deep carious lesions. In contrast, pulpal floors of greater thickness show higher levels of calcification activity. Through the cyclical changes, these maintain an increased calcification level, while those with thinner floors return to their postoperative levels, or slightly below, to achieve a reliable and steady increase nearly nine months following treatment.

Of the 50 teeth originally charted for this study, five were considered failures and were not included in the quantitative evaluations. Three of these were frank clinical or radiographic failures, and the remaining two experienced pulp exposures at the final visit, when caries was removed. The

rate of complete success, therefore, was 90 per cent.

In the future, certain improvements can be expected in the standardization of radiographic procedures and in the visual and electronic interpretation, evaluation, and measurement of radiographic records. With these advances, future investigators may monitor physiologic responses of the dental pulp, or other parts of the body, to various forms of medication or therapy, to gain important insight into human physiology and therapeutic measures of choice.

CONCLUSIONS

1. Calcium hydroxide - methyl cellulose, when used in the indirect pulp capping technique of treating deep carious lesions, initiates increased secondary dentin deposition and calcification activity, or sclerosis, as compared to the preoperative level.
2. Increased calcification activity is related to thick pulpal floors. Preoperative pulpal floor thickness has little influence on the amount of reparative dentin formed.
3. The rate of reparative dentin formation is highest during the first month and steadily diminishes with time. Calcification of the dentin overlying the pulp demonstrates a cyclical change, or "exchange," with an initial activity peak during the first month. This increase in calcification is followed by an apparent, but temporary reduction in the mineral content of the treated dentin. The reduction was followed by a steady rise in calcification level during the subsequent six - nine month observation period.
4. Measurement of longitudinal radiographic records show that apparent pulp exposures can be avoided by allowing protective secondary dentin to form, before complete caries excavation.

5. When applied to the evaluation of standardized, accurate serial radiographs, television linear and density measurement instrumentation is a useful tool in diagnosing subtle physiologic responses which are not apparent to the unaided eye.

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VITAE

Lionel Traubman II

August 8, 1939	Born in Duluth, Minnesota
1957	Graduated from University High School, Los Angeles
1957	Sigma Alpha Mu, University of California, Berkeley
1958	Phi Eta Sigma, University of California, Berkeley
1958	Interfraternity Scholastic Honor Society, University of California, Berkeley
1964	D.D.S., University of California School of Dentistry, San Francisco
1964-1965	Private Practice of Pedodontics, San Francisco
1965-1967	Graduate School in Pedodontics, Indiana University School of Dentistry, Indianapolis
August 19, 1967	Married to Elizabeth D. Linn

PROFESSIONAL SOCIETIES

The American Dental Association

The California State Dental Association

The San Francisco Dental Society

The American Society of Dentistry for Children

Alpha Omega Professional Dental Fraternity

ABSTRACT

A CRITICAL CLINICAL AND TELEVISION RADIOGRAPHIC EVALUATION OF
INDIRECT PULP CAPPING Lionel Traubman II, San Francisco

The purpose of this study was to quantitatively measure the rate and amount of calcification and secondary dentin deposition below deep carious lesions of otherwise radiographically and clinically sound teeth treated by calcium hydroxide - methyl cellulose indirect pulp capping. Standardized, reproducible serial radiographs of 50 treated young posterior teeth were exposed preoperatively at one, three, six, nine and, in some cases, 12 months. At the final appointment, the silver amalgam restorations were removed and all residual caries was excavated. A barium sulphate radiographic indicator paste identified the pulpal floor level at the first and last appointments. Ninety per cent of the teeth studied remained asymptomatic and were not pulpally exposed. Television density and linear measurement instrumentation was utilized to register calcification changes, pulpal floor thicknesses, and secondary dentin deposition. Following treatment, increased secondary dentin deposition and calcification activity, or sclerosis, was initiated. Higher levels of calcification activity were related to increased thickness of pulpal floors, but this dimension had little influence on the total amount of reparative dentin formed. The rate of reparative dentin formation was highest during the first month and steadily diminished with time. Calcification activity experienced a cyclical change, or "exchange," with an initial activity peak. This was followed by an apparent, but temporary mobilization of mineral content out of the affected dentin.

With time, a steady rise in calcification level was observed. Measurement of longitudinal records showed that apparent pulp exposures can be avoided by allowing significant amounts of protective secondary dentin to form, before complete caries excavation.